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# U.S. DEPARTMENT OF ENERGY
# FEDERAL ASSISTANCE PROGRAM/PROJECT STATUS REPORT



**1. Program/Project Identification No.** DE-FC07-96ID13439

**2. Program/Project Title** Low VOC Drying of Lumber & Wood Panel Products

**3. Reporting Period** 7-1-97 through 6-30-98


**4. Name and Address**
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**5. Program/Project Start Date** 7-1-96

**6. Completion Date** 6-30-99

**7. Approach Changes**

DOE/ID/13439-T6

[X] None

**8. Performance Variances, Accomplishments, or Problems**

We are roughly 3 months behind schedule because of personnel changes.

[ ] None

**9. Open Items**

[X] None

**10. Status Assessment and Forecast**

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[X] No Deviation from Plan is Expected

**11. Description of Attachments**

[ ] None

Annual Progress Report

**12. Signature of Recipient and Date**

Sujit Banerjee 7-21-98

**13. Signature of U.S. Department of Energy (DOE) Reviewing Representative and Date**

**Low VOC Drying of Lumber and Wood Panel Products**

**(DE-FC07-96ID13439)**

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**Progress Report No. 8**

**(Annual Summary)**

**July 1998**

CONTENTS

*ABSTRACT*

This study was initiated by an IPST finding that heating softwood in a low-headspace environment removed much of the VOCs without removing the water. Hence, one could potentially remove VOCs from wet wood, capture them as a product, and then dry the VOC-depleted wood conventionally with little or no VOC controls. Highlights of this year's efforts are itemized below.

- VOC extraction is caused by the action of microwave (or RF) itself, and not because of ancillary heat generation.
- Work with isotopically labeled water shows that microwaving promotes access of water to structured regions inside the wood matrix.
- The drying rate of lumber is not affected by low-headspace RF treatment.
- Low-headspace RF treatment does not significantly alter strength parameters (MOE, MOR, shear, tensile).
- RF treatment of OSB flakes leads to rapid release of turpentine.
- The small amount of steam generated during RF irradiation is sufficient to remove the turpentine released from the low-headspace vessel.
- An acceptable mass balance was achieved between the turpentine present in green lumber, and the sum of that released during RF treatment, lost during drying, and remaining in the dry wood.
- Proportionately more pinene is lost from sapwood than from heartwood during drying.
- A theoretical model successfully reproduces the temperature and moisture-release profiles of green wood. VOC release from dry wood has also been modeled.
- A small-scale pilot kiln loaned to us by American Kiln is being set up.
- Delayed venting in kiln drying, which is equivalent to exposing wood to steam for longer periods, leads to lower VOC release.
- Drying core samples taken monthly from 12 loblolly pine trees show that VOC releases have little or no seasonal dependence.
- VOC releases are not dependent upon the height at which the sample was taken from the tree.
- A mechanism is proposed for VOC loss under low-headspace irradiation. Most of the VOCs released originate from the surface. There are two routes for VOC emission from wood. One is through simple vaporization, which occurs from dry wood. The other is mediated by water, and takes place during early drying. RF/microwave promotes the second route.

Institute of Paper Science and Technology

## *INTRODUCTION*

This study was initiated by an IPST finding that heating softwood in a low-headspace environment removed much of the VOCs without removing the water. This offered the possibility of removing VOCs from wet wood, capturing them as a product, and then drying the VOC-depleted wood conventionally with little or no VOC controls. Two means of low-headspace heating were explored: steam and radiofrequency (RF). It was found in the previous year, that while both steam and RF were able to drive out VOCs, steam was impracticably slow for lumber. Hence the effect of RF or microwave on wood was the principal focus of the work reported here. Finally, in order to understand the mechanism of VOC release, the transport of the VOCs in wood was studied, together with the seasonal effects that influence VOC concentration in trees.

## *EFFECT OF IRRADIATION ON WOOD PROPERTIES*

### *Effect of microwaving on wood structure*

**Table 1: VOC emissions from drying microwaved wood[1]**

| microwave | VOC (μg/g) (green basis) |
|---|---|
| control | 857 |
| 1200 W, 1 min. | 145 |
| | |
| control | 767 |
| 1200 W, 1 min. | 266 |
| | |
| control | 536 |
| 600 W, 3 min. | 329 |

[1]at 130°C over 60 minutes

Unlike thermal heating where the heat moves from the surface of the wood to the interior, microwave or radiofrequency (RF) heating transfers energy to the entire wood matrix. Paired sets of OSB flakes (2-3 g) were prepared, and one set from each pair was microwaved in a Teflon cylinder (1¾" dia. x 4" length) fitted with a screw cap with a small opening that accommodated a fiberglass thermocouple. Damp sponge inserts were positioned at both ends of the cylinder in order to prevent moisture loss from the wood. Both microwaved and control flakes were dried, and the VOCs released during drying are compared in Table 1. Clearly, emissions from the microwaved wood are greatly reduced. Hence, brief microwaving under low-headspace conditions extracts much of the VOCs while retaining the water in the wood. As observed with steam, microwaving reduces the intensity of the initial VOC signal, indicating that the VOCs closer to the surface are preferentially removed.

Microwaving under open conditions, i.e. without the low-headspace restriction leads to the opposite result in that water is lost, but the VOCs are mostly retained in the wood. Since the major difference between the low-headspace and the open experiments is the retention of water in wood in the former, water must assist VOC removal under low-headspace conditions. Simply put, the hot water confined in the wood by the low-headspace constraint promotes VOC release from wood. Water strongly absorbs microwave energy, whereas energy absorption by wood is much weaker, i.e. dry wood is not a lossy material. We hypothesize that without the headspace limitation, the water or steam moves quickly out of the flake before it is able to extract the VOCs from the wood. Hence, either VOC or water release can be selected by keeping the headspace open or closed. We do not imply that VOCs can only be removed through interaction with water; simple evaporation must also be a mechanism. However, water can play a pivotal role in extracting VOCs, and control of its residence time in wood provides options in VOC control.

Some of the VOC loss in Table 1 could have been induced by the steam generated as opposed to the effect of microwave. An allocation was made by placing one half of a paired set of

| **Table 2: VOC emissions after boiling water treatment** | | |
|---|---|---|
| **heating time (min.)** | **weight loss (%) during drying** | **VOC (µg/g) green basis** |
| 0 (control) | 43.79 | 612 |
| 5 min. | 44.78 | 582 |
| | | |
| 0 (control) | 50.74 | 603 |
| 10 min. | 47.03 | 575 |
| | | |
| [1]at 130°C over 60 minutes | | |

flakes in the Teflon cylinder (with the wet sponge inserts) which was then immersed in boiling water for 5 or 10 minutes. The other half was used as a control. Both steamed and control flakes were then processed in the tube furnace. The results, shown in Table 2, demonstrate that the VOCs decrease marginally, if at all.

In order to ensure that the better performance of microwave was not due to a higher flake temperature, one of a paired set of flakes was microwaved, and the other was immersed in boiling water. A thermocouple was placed inside the Teflon cylinder for the boiling water experiments, and the temperature was monitored continuously. For the microwave work the temperature was taken just after microwaving. The results in Table 3 clearly show that the flakes reach a higher temperature in the 5-10 minute boiling experiment than during the 1-minute microwaving. Thus, the higher VOC loss in the Table 1 microwave work is *not* due to a higher temperature, but to the action of microwave itself. As a final comparison, VOCs from microwaved flakes and those exposed to heat were compared directly. One half of a paired set of flakes was microwaved in the Teflon cylinder; the other was exposed to boiling water. Both sets were then dried and their VOCs measured. The comparison in Table 4 demonstrates that much more VOC is lost during microwaving. Hence, the VOC loss in Tables 1 and 4 is induced by the microwave irradiation, and not by an ancillary increase in temperature.

*Effect of microwaving on water movement*

In order to determine the degree to which microwaving moves water within wood, green pine blocks (2" x 1"x 1") were dried to different moisture levels at 120°C, immersed in $D_2O$ (>99% isotopic content) for different periods at room temperature, and were then cut in halves. One half was wrapped in plastic and microwaved at 110 W for 30 minutes, until the internal

| **Table 3: Comparison of temperature profiles during boiling and microwaving** | | | | |
|---|---|---|---|---|
| **microwave** | | | **boiling water** | |
| **power (W)** | **min.** | **temperature (°C)** | **min.** | **temperature (°C)** |
| 300 | 1 | 72 | 1 | 60 |
| 300 | 2 | 82 | 2 | 75 |
| 300 | 3 | 89 | 3 | 85 |
| 300 | 4 | 89 | 4 | 90 |
| | | | 5 | 91 |
| 600 | 1 | 79 | 6 | 92 |
| 600 | 2 | 90 | 7 | 94 |
| 600 | 3 | 90 | 8 | 95 |
| | | | 9 | 96 |
| 1200 | 1 | 84 | 10 | 96 |
| 1200 | 2 | 93 | 20 | 96 |

| Table 4: VOC emissions at 130°C over 60 minutes | | | |
|---|---|---|---|
| microwave treatment | boiling water treatment | weight loss (%) | VOC (μg/g) wet basis |
| 600 W, 2 min. | | 47.70 | 239 |
| | 5 min. | 45.84 | 352 |
| | | | |
| 600 W, 2 min. | | 35.66 | 424 |
| | 5 min. | 38.35 | 799 |
| | | | |
| 600 W, 2 min. | | 41.41 | 215 |
| | 5 min. | 38.62 | 514 |

| Table 5: Isotopic content of water released from wood | | | |
|---|---|---|---|
| MC (%)[1] | soaking period (days) | percent deuterium (σ)[2] | |
| | | control | microwaved |
| 125 | 5 | 48 (15) | 47 (8) |
| 44 | 10 | 56 (16) | 47 (5) |
| 24 | 2 | 60 (4) | 49 (7) |
| 0 | 5 | 61 (7) | 45 (3) |
| | | | |
| [1]dry basis MC of the wood being microwaved; [2]averaged from 5 samples | | | |

temperature (as measured by a fiber optic probe) reached 100°C. The field was then shut off for 15 minutes, and the cycle was repeated until the wood experienced 30 minutes of actual microwaving. The wrap retained the water in the wood. The other half served as a control. Fibers taken from just inside the wet surface from five regions along the length of each piece were then analyzed by mass spectrometry with a direct insertion probe. The ion chromatograms of the three isotopic forms of water, namely $H_2O$, HOD, and $D_2O$, tracked one another as the wood was heated inside the spectrometer. In other words, the $H_2O$: HOD: $D_2O$ proportion remained constant throughout, indicating that all three forms of water were bound equally strongly to the wood, and that fractional distillation did not occur.

The water released from green wood (MC: 125%) had the same isotopic composition regardless of whether or not the wood was microwaved (Table 5), indicating that the exchangeable protons in wood were not affected by microwaving. However, with the use of progressively drier wood, the water released from fibers taken from the microwaved wood was of lower isotopic content, which means that microwaving opened up the wood structure and allowed greater isotope exchange. In other words, microwaving increases access of the exchangeable protons in wood tissue to $D_2O$. The exchangeable protons in dried wood are mostly those sited on hydroxyl groups, and the difference in isotopic exchange is the greatest for the dried wood. This must mean that as wood dries, internal hydrogen bonding restricts access of the $D_2O$ to the hydroxyl protons. Presumably the energy transferred to water upon microwaving is sufficient to at least partially overcome this barrier. The effect resembles the hysteresis that occurs for moisture sorption to green and dried wood. Analogous isotope exchange work with $D_2O$ has been previously conducted (1-8) to determine the accessibility of cellulose to water.

Energy transferred to water constrained in wood is probably dissipated by increased thermal motion of the water within the wood matrix. The isotopic work illustrates this quite well; under irradiation, $D_2O$ is able to access hydrogen-bonded areas that are otherwise excluded. The contrast between open and low-headspace microwaving demonstrates that hot water, when forced to remain in the wood through the low-headspace restriction, helps to remove the VOCs out of wood. Thus, there must be at least two means of VOC removal from wood during conventional drying. Water must be at least partially responsible for VOC loss from green wood during early drying. VOC removal from dry wood is driven by vapor pressure considerations (9,10).

The VOC material is concentrated in hydrophobic regions within the wood matrix. We believe that transferring energy to water while constraining it to remain in the wood promotes transport of the VOCs to hydrophilic zones. Alexiou et al (11) have shown that pre-steaming *Eucalyptus* mobilizes heartwood extractives, probably by allowing water greater access to cell walls. Irradiating the wood under low-headspace conditions appears to promote this access. The air:water Henry's Law Constant, the distribution coefficient between the two media, is estimated to be 4 at room temperature. It is likely to be much higher at 95°C, since the vapor pressure rises much more quickly with increasing temperature (12) than does solubility (13). Microwave is much more efficient than thermal heating probably because it deposits energy principally to the water, as opposed to the entire wood structure. Also, the sapwood is likely to heat up more rapidly than the heartwood owing to its higher water content, and the resulting temperature imbalance may promote mixing. The detailed mechanism of the process is not known, and is under study.

***Effect of RF-irradiation on drying rate***

In order to determine the extent to which RF-treatment alters pit structure, control and RF-treated samples (2"x3.25"x22" pieces) were examined by SEM, after solvent-exchange with acetone, and air drying. The wood was irradiated for 30 minutes with Georgia Power's Stray-field unit, with the field being cycled to keep the surface temperature at 90-100°C. SEM photographs of sapwood samples taken just below the surface demonstrated that RF-treatment induced pit aspiration. Each board was cut in two, and each half was dried at 70°C and 90°C under an

**Table 6: Replicate drying rates of (2"x3.25"x11") wood at 70°C**

| time (hr) | MC | | MC | | MC | |
|---|---|---|---|---|---|---|
| | control | RF | control | RF | control | RF |
| 0 | 69.0 | 53.3 | 58.4 | 44.9 | 97.8 | 101.2 |
| 2 | 62.9 | 49.3 | 54.0 | 39.3 | 94.5 | 97.7 |
| 5 | 52.4 | 42.5 | 46.7 | 31.6 | 85.3 | 88.2 |
| 7 | 45.7 | 37.4 | 41.6 | 26.9 | 78.3 | 81.2 |
| 9 | 39.7 | 32.3 | 36.3 | 23.0 | 71.1 | 73.7 |
| 21 | 18.6 | 16.6 | 18.7 | 14.1 | 43.0 | 38.1 |
| 27 | 14.0 | 13.3 | 15.0 | 11.6 | 29.6 | 25.1 |
| 36.5 | 10.4 | 10.2 | 11.5 | 9.0 | 19.1 | 16.2 |
| 51.5 | 6.6 | 6.8 | 7.7 | 6.1 | 10.6 | 9.6 |
| 119 | 1.8 | 1.9 | 2.1 | 1.9 | 2.3 | 2.2 |

| Table 7: Drying rates (MC) of (2"x3.25"x11") wood at 90°C | | | | | | |
|---|---|---|---|---|---|---|
| time (hr) | MC | | MC | | MC | |
| | control | RF | control | RF | control | RF |
| 0 | 71.1 | 56.1 | 56.1 | 44.3 | 105.0 | 101.0 |
| 3 | 55.2 | 44.7 | 45.4 | 29.5 | 93.1 | 90.7 |
| 7.5 | 34.3 | 25.7 | 30.3 | 16.5 | 68.8 | 64.3 |
| 10 | 26.8 | 19.4 | 25.1 | 13.5 | 58.6 | 51.6 |
| 11.5 | 22.6 | 16.6 | 22.1 | 11.8 | 52.5 | 43.9 |
| 18.75 | 11.7 | 9.8 | 12.7 | 7.0 | 31.8 | 19.4 |
| 21.5 | 9.5 | 8.1 | 10.5 | 5.7 | 25.8 | 15.3 |
| 24.5 | 7.5 | 6.6 | 8.5 | 4.5 | 20.1 | 12.0 |
| 29.5 | 5.1 | 4.7 | 6.1 | 3.1 | 13.1 | 8.3 |
| 34 | 3.6 | 3.4 | 4.4 | 2.2 | 9.1 | 6.0 |
| 43 | 1.6 | 1.6 | 2.2 | 1.4 | 4.0 | 2.6 |

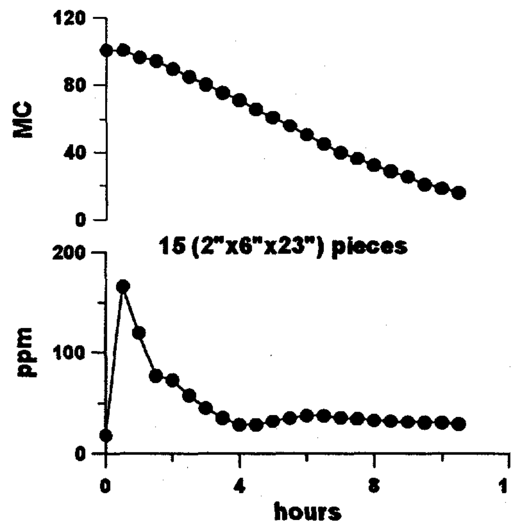


**Figure 1: Drying profiles of larger pieces**

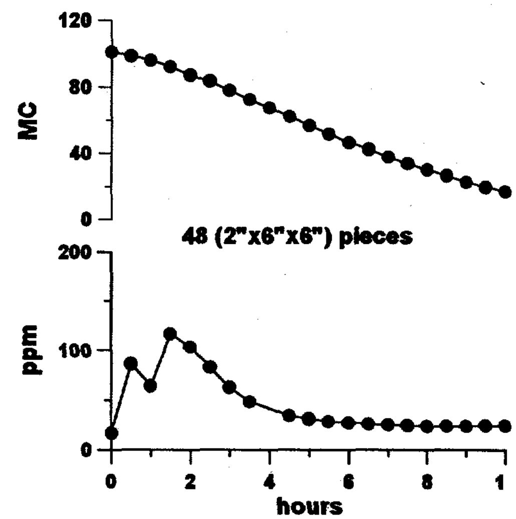


**Figure 2: Drying profiles of smaller pieces**

airflow of 4 lpm. The drying rate data shown in Tables 6 and 7 demonstrate that although the RF-treated wood reaches the fiber saturation point slightly earlier than does the control (because of its lower initial MC), the overall drying rate is not materially affected by irradiation.

In a larger-scale experiment, 24 pieces of lumber were irradiated in our low-headspace reactor for approximately 30 minutes each, and shipped to Mississippi State University for testing with a control set. In order to understand the factors that influence VOC release from drying lumber, matching pieces were dried until the load reached about 15% MC. In order to determine the importance of edge effects, parallel measurements were made with end-coated pieces. Dry and wet bulb temperatures were 245°F, and 180°F, respectively. The results (all for matched sets of wood) are presented in Figures 3 and 4, and summarized in Table 8.

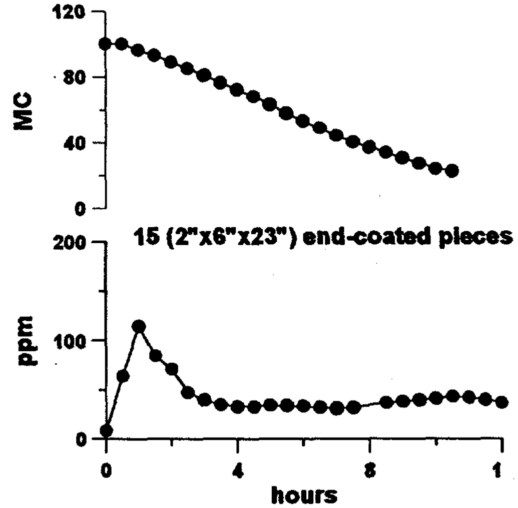


**Figure 3: Drying profiles of end-coated larger pieces**

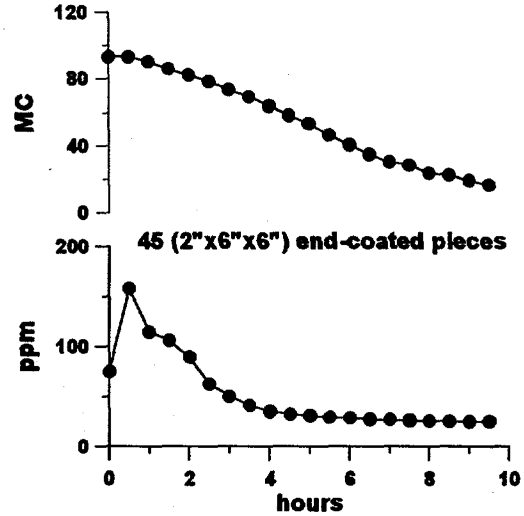


**Figure 4: Drying profiles of end-coated smaller pieces**

| Table 8: Summary of drying results | | | | |
|---|---|---|---|---|
| no. of pieces | dimensions | average VOC | total VOC (lbs/ton) | average drying rate (MC% per hr.) |
| 15 | 2"x6"x23" | 477 | 2.62 | 5.46 |
| 48 | 2"x6"x6" | 447 | 2.80 | 9.06 |
| 15 (end-coated) | 2"x6"x23" | 433 | 2.63 | 7.73 |
| 48 (end-coated) | 2"x6"x6" | 518 | 2.84 | 9.05 |

Comparison of the first two entries in Table 8 shows that although reducing furnish size does not materially affect the quantity or rate of VOC release, the moisture is lost faster from the smaller pieces. First, this demonstrates a difference in the mechanism of release of moisture and VOC from lumber at these temperatures. A similar difference was observed in earlier work with particle (10), where the moisture and VOC profiles were different at 220°F, but converged at 320°F. That moisture loss occurs faster from smaller pieces is to be expected, since water preferential flows in the longitudinal direction. However, the constancy of the VOC emissions suggests that VOCs are lost from all surfaces, and are not transported by water under these conditions.

*Effect of RF-irradiation on strength*

Twenty five Southern pine 2" x 6" x 8' boards were machined into 2" x 4" pieces, and then cut into matched pairs. One of the two was irradiated with RF in our low headspace reactor, while the other served as a control. Both sets were dried under a conventional temperature-time based schedule. The lumber was removed from the kiln when it reached an average dry-basis MC of 15%. After drying, the moisture was equalized to about 12%. Two boards from each charge warped during drying. The lumber was machined into test specimens, and tests were performed as per ASTM Section D-143 and Appendix Q. Temperature and other changes are recorded in Table 9. Tables 10 and 11 compare strengths of the control and irradiated boards, respectively. Tensile measurements were made on two samples cut from each board; the data are separated into stronger and weaker groups respectively.

Paired T-tests (single-tail) with $\alpha=0.5$ showed minor differences in shear, MOE, and MOR. A test of hypotheses and a test through confidence intervals also showed that the null hypotheses (Ho:u=uo) for both MOE and MOR were rejected; i.e. the control and sample were significantly different. However, range and a sample mean control charts showed a possibility of a Type I error (Ho rejected when Ho is true), since the process was on both sides of the process norm. There was one point in the range control chart which was outside the upper $3\sigma$ limit for MOE, and three in the sample mean chart which lay outside the $3\sigma$ limit for MOR. However, we cannot conclude that the process is out of control since nearly every other point crossed the centerline. The results for tests of confidence intervals were different to the test of hypotheses. The null hypotheses were not rejected in any of the strength tests. Hence, our overall conclusion is that RF-treatment does not significantly affect strength.

**Table 9: Changes in temperature and other properties during RF irradiation**

| ID | time to reach 100°C | ave. interior temp (°C) | ave. surf. temp (°C) | max int. temp (°C) | green density (g/cm$^3$) | wt. loss (%) |
|---|---|---|---|---|---|---|
| T-1 | 9 | 111.9 | 98.8 | 117.9 | 0.843 | 5.0 |
| T-2 | 14 | 102.8 | 96.2 | 104 | 0.833 | 6.5 |
| T-3 | 6 | 104 | 91.1 | 111.4 | 1.021 | 5.6 |
| T-4 | 9 | 106.8 | 95.8/ | 120 | 0.749 | 6.5 |
| T-5 | 11 | 106.9 | 99.4 | 113.1 | 0.883 | 6.5 |
| T-6 | 9 | 105.5 | 97.4 | 110.4 | 0.867 | 4.6 |
| T-7 | 9 | 101.3 | 97.6 | 102.4 | 0.870 | 3.9 |
| T-8 | 7 | 101.6 | 98.5 | 103.5 | 0.951 | 6.2 |
| T-9 | 7 | 102.2 | 97.4 | 105.9 | 0.730 | 9.7 |
| T-10 | 15 | 109.3 | 97.8 | 123.7 | 0.716 | 8.6 |
| T-11 | 9 | 102.9 | 95.3 | 111.2 | 0.916 | 4.8 |
| T-12 | 8 | 108.1 | 96.9 | 117.8 | 0.837 | 5.7 |
| T-13 | 7 | 101.4 | 98.1 | 103.1 | 0.826 | 8.0 |
| T-14 | 6 | 108.4 | 97.5 | 124.0 | 0.649 | 7.4 |
| T-15 | 5 | 107.8 | 95.5 | 115 | 0.902 | 4.1 |
| T-16 | 11 | 105.5 | 95.7 | 110 | 0.792 | 4.7 |
| T-17 | 7 | 105.8 | 95.7 | 112.8 | 0.854 | 4.9 |
| T-18 | 10 | 103.7 | 98.4 | 106.4 | 0.758 | 5.0 |
| T-19 | 14 | 102.8 | 97.6 | 104.2 | 0.982 | 6.2 |
| T-20 | 6 | 107.0 | 96.8 | 112.3 | 0.674 | 8.3 |
| T-21 | 7 | 104.6 | 96.8 | 109.9 | 0.787 | 7.2 |
| T-22 | 6 | 115.9 | 96.1 | 121.7 | 0.596 | 6.8 |
| T-23 | 9 | 102.7 | 94.7 | 108.4 | 0.744 | 7.8 |
| average | 8.7 | 105.6 | 96.7 | 111.7 | 0.817 | 6.3 |

| Table 10: Strength and other properties for the control boards | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | moisture content % | density g/cc | max com-press[1] | MOE[1] | MOR[1] | shear[1] | tensile[1] A | B |
| 1 | 0.114504 | 0.532732 | 6518 | 1130953 | 10276 | 1872.08 | 9202.956 | 6359.909 |
| 2 | 0.112345 | 0.408346 | 6457 | 1033942 | 7870 | 1439.556 | 11333.48 | 6573.03 |
| 3 | 0.113962 | 0.527279 | 7209 | 1808622 | 13956 | 1741.248 | 15168.25 | 11363.64 |
| 4 | 0.099662 | 0.39199 | 5938 | 1255213 | 8913 | 1065.408 | 12178.21 | 10288.99 |
| 5 | 0.124312 | 0.573609 | 7906 | 1297280 | 11377 | 1897.736 | 11400.21 | 8318.356 |
| 6 | 0.113213 | 0.483118 | 5274 | 1425754 | 9296 | 1772.791 | 11449.35 | 10348.82 |
| 7 | 0.113332 | 0.472256 | 8056 | 2005898 | 13061 | 1149.152 | 18753.78 | 7973.286 |
| 8 | 0.121182 | 0.532034 | 7521 | 1593309 | 12337 | 1524.273 | 14584.96 | 12446.28 |
| 9 | 0.119167 | 0.519489 | 5115 | 1526608 | 13109 | 1673.813 | 14588.34 | 10520.85 |
| 10 | 0.124318 | 0.535968 | 7703 | 1662529 | 9716 | 1689.654 | 8602.821 | 8376.34 |
| 11 | 0.114518 | 0.439987 | 6614 | 1925055 | 14409 | 1168.043 | 21357.38 | 17577.84 |
| 12 | 0.114047 | 0.374444 | 5213 | 1407793 | 7765 | 1003.252 | 7431.457 | 6902.441 |
| 13 | 0.113931 | 0.455027 | 6691 | 1671271 | 10320 | 1280.291 | 16010.82 | 13410.95 |
| 14 | 0.116891 | 0.428513 | 5571 | 1396905 | 7994 | 1425.498 | 14478.11 | 11360.45 |
| 15 | 0.116844 | 0.525122 | 7733 | 1826089 | 14515 | 1878.147 | 14455.42 | 11416.46 |
| 16 | 0.115561 | 0.437717 | 5874 | 946760.7 | 6855 | 1390.597 | 16512.7 | 13463.59 |
| 17 | 0.122389 | 0.580965 | 6962 | 1265623 | 11078 | 1788.158 | | |
| 18 | 0.116959 | 0.452948 | 7672 | 1713040 | 12302 | 1596.186 | 12490.03 | 10937.28 |
| 19 | 0.113961 | 0.4929 | 5253 | 1247911 | 11048 | 1438.935 | 10944.01 | 8933.442 |
| 20 | 0.117054 | 0.469042 | 6777 | 1732571 | 9256 | 1437.734 | 17895.55 | 11251.19 |
| 21 | 0.11551 | 0.44103 | 6063 | 1548263 | 9801 | 1347.579 | 8300.477 | 8210.93 |
| 22 | 0.114286 | 0.483786 | 6268 | 1698877 | 11092 | 1423.899 | 9836.066 | 9582.097 |
| 23 | 0.12106 | 0.502143 | 6791 | 1633473 | 9633 | 1314.523 | 16468.77 | 8121.313 |
| | | | | | | | | |
| [1]psi | | | | | | | | |

***RF pre-treatment of pine flakes***

Green pine flakes (OSB flakes) received from Dudley, NC, on 3.25.98 were packed inside our low-headspace container and irradiated at 0.9A for 3 minutes, at which point the flake temperature reached 100°C. The power was then cycled over 12 minutes to keep the flake temperature at 90-100°C. It is estimated that the power was on for only one-third of the cycling period. A 1.2 kg charge was used, and a weight loss of 12.7% was incurred during irradiation.

Method 25A measurements made during drying both control and irradiated flakes in our tube furnace are listed in Table 12, and a typical profile is illustrated in Figure 5. Irradiation reduces VOCs by about 70%. The pinene and turpentine content of these flakes were determined after acetone extraction. The sum of all the gc signals observed was taken to be the equivalent of turpentine. The results, listed in Table 13 are similar to those in Table 12, confirming that pinene constitutes the bulk of the emissions.

| Table 11: Strength and other properties for the irradiated boards | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ID | moisture content % | density g/cc | max compress[1] | MOE[1] | MOR[1] | shear[1] | tensile[1] | |
| | | | | | | | A | B |
| 1 | 0.111227 | 0.504484 | 7332 | 1561537 | 10815 | 916.162 | 17832.45 | 13102.12 |
| 2 | 0.113507 | 0.462842 | 8850 | 1397661 | 10815 | 1635.332 | 16366.11 | 14624.22 |
| 3 | 0.113536 | 0.502658 | 7839 | 1773954 | 10815 | 1465.452 | 11854.58 | 11809.32 |
| 4 | 0.099637 | 0.443459 | 4269 | 1208551 | 10815 | 1420.062 | 7608.537 | 6578.282 |
| 5 | 0.118528 | 0.509069 | 5578 | 1100718 | 10815 | 1618.901 | 8671.613 | 6147.837 |
| 6 | 0.120452 | 0.419697 | 6070 | 1255932 | 10815 | 1277.532 | 9501.916 | 9364.607 |
| 7 | 0.118848 | 0.43621 | 7020 | 1639839 | 10815 | 1319.964 | 15059.35 | 14184.4 |
| 8 | 0.107062 | 0.462889 | 6016 | 1411309 | 10815 | 1442.882 | 13694.25 | 8555.275 |
| 9 | 0.113911 | 0.385506 | 4687 | 1231071 | 10815 | 1267.051 | 8221.851 | 7849.966 |
| 10 | 0.106176 | 0.434905 | 4058 | 720277 | 10815 | 1263.338 | 7465.021 | 7340.647 |
| 11 | 0.112117 | 0.563902 | 7405 | 1596414 | 10815 | 1692.25 | 17958.44 | 16582.75 |
| 12 | 0.118521 | 0.486986 | 6773 | 1434073 | 10815 | 1531.074 | 10804.87 | 7097.603 |
| 13 | 0.115029 | 0.633826 | 6768 | 1410910 | 10815 | 1731.866 | 17169.27 | 11301.14 |
| 14 | 0.113504 | 0.424917 | 5226 | 1202880 | 10815 | 1584.054 | 10629.53 | 9824.755 |
| 15 | 0.123926 | 0.548787 | 6581 | 1826034 | 10815 | 1656.952 | 15850.35 | 15789.7 |
| 16 | 0.112245 | 0.45891 | 5468 | 1400957 | 10815 | 960.2 | | |
| 17 | 0.112195 | 0.456512 | 6306 | 1462204 | 10815 | 1433.403 | 13114.17 | 11312.73 |
| 18 | 0.113475 | 0.409249 | 5523 | 1618265 | 10815 | 1021.698 | 9643.135 | 9142.948 |
| 19 | 0.1239 | 0.541905 | 8082 | 1331700 | 10815 | 1702.843 | 17622.75 | 13173.59 |
| 20 | 0.105401 | 0.454253 | 5058 | 1174138 | 10815 | 1073.299 | 12966.12 | 12717.25 |
| 21 | 0.107702 | 0.421954 | 6146 | 1264709 | 10815 | 1702.735 | 11338.44 | 11214.42 |
| 22 | 0.090307 | 0.429721 | 4790 | 1197173 | 10815 | 1244.104 | 12029.71 | 8481.592 |
| 23 | 0.118041 | 0.373116 | 4873 | 1140749 | 10815 | 1235.231 | 9428.073 | 7273.685 |

[1]psi

## *TURPENTINE RECOVERY THROUGH LOW-HEADSPACE HEATING*

### *Microwave heating of water and pinene*

Water or pinene (30 g.) was placed in a $\phi$1.5x4" Teflon cup fitted with a narrow-bore vent tube, and a second tube that accommodated a fiber optic temperature sensor. The unit was run at a forward power setting of 350W, and the temperature rise is recorded in Figure 6. Next, a mixture of 15 g each of water and pinene was microwaved under identical conditions. The quantity of condensate collected from the vent tube is listed in Table 14. The vapor pressure of $\alpha$-pinene at 100°C is 0.14 atm, which means that 1.2 g. of pinene should be removed with every gram of steam. Although the experimental value of 1.0 from Table 14 is lower, possibly because the system was not at 100°C throughout, it is clear that the bulk of the pinene can be carried out by a small amount of steam. Since even the small quantity of steam evolved under low head-space conditions will far exceed that of turpentine, there should be enough steam to carry out most of the turpentine released.

| Table 12: Method 25A emissions of green and irradiated flakes | |
|---|---|
| **ID** | **VOC (µg/g)** |
| ***green flakes before RF treatment*** | |
| 79-1 | 945 |
| 79-2 | 1,900 |
| 79-3 | 2,360 |
| 79-4 | 1,070 |
| PF11 | 889 |
| PF12 | 614 |
| PF13 | 605 |
| PF14 | 712 |
| **average** | **1,100 ± 600** |
| | |
| ***green flakes after RF treatment*** | |
| RFPF01 | 305 |
| RFPF02 | 356 |
| RFPF03 | 421 |
| RFPF04 | 337 |
| **average** | **360 ± 50** |

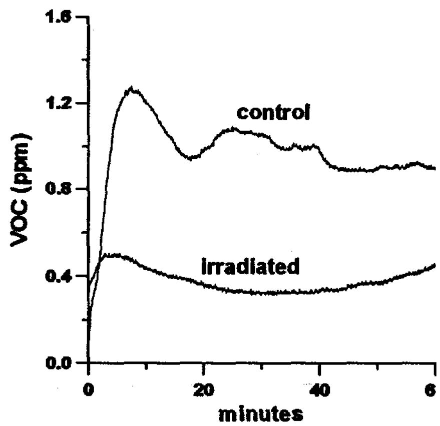


**Figure 5. VOC emissions from control and irradiated flakes**

| Table 13: Pinene content of green and irradiated flakes | | |
|---|---|---|
| **ID** | **pinene (µg/g, dry basis)** | **turpentine(µg/g, dry basis)** |
| ***green flakes before RF treatment*** | | |
| WPF01 | 1,714 | 1,769 |
| WPF02 | 625 | 677 |
| WPF03 | 842 | 878 |
| **average** | **1,060** | **1,110** |
| ***green flakes after RF treatment*** | | |
| WRFPF01 | 518 | 560 |
| WRFPF02 | 445 | 473 |
| WRFPF03 | 232 | 254 |
| **average** | **398** | **429** |

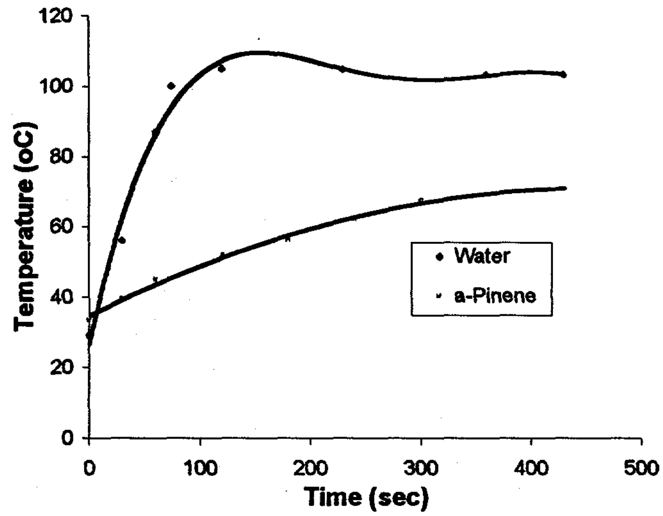


**Figure 6. Temperature profiles for water and pinene.**

| **Table 14: Condensate from irradiating a 1:1 water: pinene mixture** | | | |
|---|---|---|---|
| **time (sec)** | **temperature (°C)** | **condensed water (g.)** | **condensed pinene (g.)** |
| 0 | 31.2 | | |
| 10 | 45 | | |
| 20 | 56.2 | | |
| 30 | 71.8 | | |
| 50 | 94 | | |
| 60 | 102.1 | | |
| 210 | 107 | 5 | 4 |
| 360 | 108.2 | 6.5 | 6 |
| 420 | 109.4 | 7.54 | 7.61 |

***Recovery of turpentine from RF treatment of lumber***

A preliminary experiment was conducted to determine the quantity and purity of turpentine that could be separated during the RF operation. Eight 2 x 3.25 x 22" pieces of loblolly pine obtained from Mississippi State University were treated by RF (30 minutes, 0.9A) within two days of receipt, with the emissions being collected in a cold water trap. Since our low-headspace chamber can only accommodate one board at a time, the irradiation was performed sequentially, with the same trap being used to collect all the emissions. A total of 8.4 g. of turpentine was found floating on the surface of the water trap, which corresponds to 1.1 (g/kg, dry basis). Pinene was the main constituent, as illustrated in Table 15.

| Table 15. Composition of recovered turpentine | |
|---|---|
| | content (%) |
| α-pinene | 67 |
| camphene | 1.0 |
| β-pinene | 25 |
| myrcene | 1.3 |
| limonene | 3 |
| α-terpineol | 1.8 |
| other | 0.8 |

*Mass balance of VOC released from and retained in wood during RF-treatment*

We have shown in previous work that a substantial amount of turpentine is released during low-headspace RF-treatment of wood. In order to establish a mass balance, 2" x 4" x 44" pieces of pine received from MSU on 12.12.97 were each cut into two 2" x 3.25" x 22" pieces, and RF-treated two weeks later. The power setting of the Strayfield RF unit was at 0.9A, and the field was cycled in order to keep the surface temperature of the wood between 90 and 100°C. The total treatment time was 30 minutes, including the period during which the RF power was turned off during processing. Pinene was collected in two instances in a 200 mL methanol trap attached to the low-headspace reactor described in report #4. Table 16 lists the weight changes and the VOCs emitted during both irradiation and the subsequent drying (conducted at MSU). Subsamples of the dried wood, EE and F, taken from the locations illustrated in Figure 7 were extracted by acetone and analyzed by GC; these results are provided in Table 17.

The differences in VOC released during drying between RF and control samples is least for the AA and B series in Table 16, which contained knots. For the other samples, RF-treatment reduced VOC emissions by an average of 56%. The VOC mass balance for samples EE and F where the VOCs were measured after each operation is provided in Table 18. The agreement is within 20%, indicating that the VOC removed during RF-treatment would otherwise be principally lost during drying.

A second set of measurements was run with larger (2"x4"x48") pieces of board. Wood obtained from MSU on 1.22.98 was cut into two pieces (2"x3.25"x22") for RF treatment four days after receipt. The middle 4" block left from each piece was extracted with acetone, which was then analyzed by gc for pinene and resin/fatty acids. The results are provided in Table 19. One of the two remaining pieces were RF-treated; the other was used as a control. Both pieces were then returned to MSU where they were dried, and the VOCs measured. The results are provided in Table 20. As noted earlier, the first VOC peak observed in the control sample was reduced or eliminated for the RF-treated board.

Sub-samples taken from two RF-treated pieces were analyzed for their pinene and resin/fatty acids content. The results are provided in Table 21. Note that the pinene is depleted along the edges, whereas resin acid levels are uniform across the board. The pinene remaining in wood after drying was extracted by acetone and analyzed by GC; the results are listed in Table 22. It is evident from Table 22 that the residual turpentine in dry wood and that released during drying is much less than that in green wood. The reasons as to why a good mass balance was obtained in the preceding experiment and not in this one are unknown. It is possible that some of the difference is due to VOC loss from the hot wood during the cool down period (when the VOCs were not measured), and during transport of the wood from MSU to IPST.

**Table 16: Release of water and pinene during irradiation**

| ID | wood weight (g.) | | | pinene released during RF (μg/g)[3] | VOC (μg/g) released during drying[3] |
|---|---|---|---|---|---|
| | green | post-RF | dried[1] | | |
| AA-1 (control)[2] | 1882 | - | 867 | - | 253 |
| AA-2[2] | 1820 | 1580 | 859 | - | 469 |
| B-1 (control)[2] | 2320 | - | 1311 | - | 885 |
| B-2[2] | 2266 | 2042 | 1031 | - | 727 |
| C-1 (control) | 1786 | - | 971 | - | 813 |
| C-2 | 1792 | 1502 | 961 | - | 385 |
| EE-1 (control) | 2320 | - | 1311 | - | 690 |
| EE-2 | 2372 | 1946 | 1284 | 717 | 279 |
| F-1 (control) | 2294 | - | 1048 | - | 804 |
| F-2 | 2328 | 1988 | 1062 | 593 | 371 |

[1]Dried at 125°C dry bulb temperature (82°C wet bulb) for 11.5 hr under an airflow of 12 lpm. [2]These samples contained knots. [3]dry basis

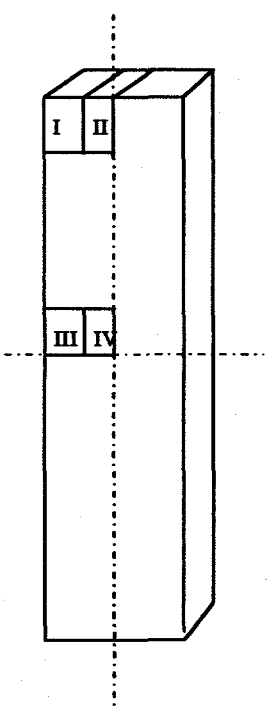


**Figure 7. Location of subsamples taken for solvent extraction.**

**Table 17: Residual pinene in dried wood**

| control | | RF-treated | |
|---|---|---|---|
| **ID** | **pinene (μg/g)** | **ID** | **pinene (μg/g)** |
| EE-1 I | 83 | EE-2 I | 13 |
| EE-1 II | 82 | EE-2 II | 25 |
| EE-1 III | 98 | EE-2 III | 209[1] |
| EE-1 IV | 103 | EE-2 IV | 21 |
| **average** | **92** | **average** | **67** |
| | | | |
| F-1 I | 192 | F-2 I | 75 |
| F-1 II | 249 | F-2 II | 129 |
| F-1 III | 224 | F-2 III | 33 |
| F-1 IV | 596 | F-2 IV | 34 |
| **average** | **315** | **average** | **68** |

[1]the high result could be caused by a knot.

| Table 18: Mass balance of VOCs (μg/g) | | | | |
|---|---|---|---|---|
| ID | VOC removed during | | VOC remaining in wood | total VOC |
| | RF | drying | | |
| EE (control) | | 690 | 92 | 782 |
| EE (RF) | 717 | 279 | 67 | 1060 |
| | | | | |
| F (control) | | 804 | 315 | 1120 |
| F (RF) | 593 | 371 | 67 | 1030 |

| Table 19: Organics content (dry basis) of lumber before RF treatment[1] | | | |
|---|---|---|---|
| ID | pinene (μg/g) | turpentine (μg/g)[2] | resin/fatty acids (μg/g) |
| 1A | 1900 | 2230 | 17000 |
| 1B | 5860 | 6430 | 21700 |
| 1C | 6660 | 7210 | 21400 |
| 1D | 20100 | 26100 | 35500 |
| 1E | 2640 | 4890 | 22900 |
| 1F | 8680 | 13700 | 21300 |
| 1G | 2730 | 3020 | 14100 |
| 1H | 2780 | 4660 | 13500 |
| | | | |
| [1]average of 2 determinations; [2]includes other terpenes | | | |

| Table 20: Weight loss and VOC emissions of RF-treated wood | | | | |
|---|---|---|---|---|
| ID | weight (g.) | | | VOC (μg/g, dry basis)[1] |
| | green | post-RF | OD | |
| 1A-1 (control) | 1890 | - | 947 | 268 |
| 1A-2 | 1828 | 1680 | 885 | 145 |
| 1B-1 (control) | 1920 | - | - | - |
| 1B-2 | 1962 | 1860 | - | - |
| 1C-1 (control) | 2016 | - | - | - |
| 1C-2 | 2006 | 1892 | - | - |
| 1D-1 (control) | 1882 | - | 1143 | 277 |
| 1D-2 | 1590 | 1380 | 1057 | 132 |
| 1E-1 (control) | 2065 | - | 975 | 250 |
| 1E-2 | 2048 | 1900 | 992 | 132 |
| 1F-1 (control) | 1701 | - | 991 | 1989 |
| 1F-2 | 1646 | 1472 | 930 | 608 |
| 1G-1 (control) | 2207 | - | 1009 | 350 |
| 1G-2 | 2260 | 2118 | 999 | 154 |
| 1H-1 (control) | 2216 | - | 1064 | 281 |
| 1H-2 | 2218 | 2078 | 994 | 154 |
| | | | | |
| [1]dried at 124°C for 11 hrs at MSU | | | | |

| Table 21: Organics (μg/g, dry basis) in RF-treated wood (before drying) | | | | |
|---|---|---|---|---|
| ID | location | pinene | turpentine[1] | resin/fatty acids |
| 1B2-E1 | edge | 1400 | 1590 | 21700 |
| 1B2-B | off-center | 2030 | 2300 | 21900 |
| 1B2-M | center | 2000 | 2250 | 20400 |
| 1B2-E2 | edge | 1460 | 1700 | 21200 |
| **average** | | **1720** | **1960** | **21300** |
| 1C2-E1 | edge | 1930 | 2270 | 24500 |
| 1C2-B | off-center | 2320 | 2700 | 23500 |
| 1C2-M | center | 2480 | 2830 | 15100 |
| **average** | | **2240** | **2600** | **21000** |
| | | | | |
| [1]includes other terpenes | | | | |

| Table 22: Organics in dried wood (μg/g, dry basis) | | | | | |
|---|---|---|---|---|---|
| ID | pinene | turpentine[1] | turpentine in green wood | remaining turpentine (% of green wood) | VOC released during drying |
| 1E1-E | 123 | 251 | | | |
| 1E1-B | 282 | 418 | | | |
| 1E1-M | 89 | 286 | | | |
| **avg** | **165** | **318** | **4890** | **6.5** | **250** |
| 1E2-E | 10 | 87 | | | |
| 1E2-B | 46 | 287 | | | |
| 1E2-M | 93 | 287 | | | |
| **avg** | **50** | **230** | **4890** | **4.7** | **132** |
| 1G1-E | 24 | 170 | | | |
| 1G1-B | 14 | 89 | | | |
| 1G1-M | 763[2] | 1113[2] | | | |
| **avg** | **19** | **130** | **3020** | **4.3** | **350** |
| 1G2-E | 26 | 240 | | | |
| 1G2-B | 12 | 192 | | | |
| 1G2-M | 14 | 89 | | | |
| **avg** | **17** | **174** | **3020** | **5.8** | **154** |
| 1H1-E | 24 | 345 | | | |
| 1H1-B | 25 | 420 | | | |
| 1H1-M | 45 | 456 | | | |
| **avg** | **31** | **407** | **4661** | **8.7** | **281** |
| 1H2-E | 6 | 82 | | | |
| 1H2-B | 5 | 199 | | | |
| 1H2-M | 6 | 328 | | | |
| **avg** | **6** | **203** | **4661** | **4.4** | **159** |
| | | | | | |
| [1]includes other terpenes; [2]excluded, due to the possible presence of a knot. | | | | | |

*RF pretreatment of pine lumber*

Pine lumber and its associated sawdust was collected from the G-P sawmill in Warrenton, GA on 10.13.97. The original pieces were trimmed to 1 7/8" x 3 ¼" x 48" in order to fit into our tube. The wood was irradiated for 30 min, with the power being cycled to keep the surface at 100°C. Emissions during irradiation were collected in 200 mL of iced methanol. In one case, emissions were collected in two stages of 5 and 11 minutes, respectively. Particle was used in place of lumber in one experiment. Weight loss data and the amount of turpentine collected from 9 separate pieces are listed in Table 23. Four of the pieces (the RFE series in Table 23) were then cut longitudinally as shown in Figure 8. Samples taken from the marked zones in Figure 8, were both solvent-extracted (acetone), and heated for 1 hour at 130°C with the emissions monitored by FIA. Controls (without irradiation) were run from a section taken from the same piece of wood. The results presented in Table 24 show that the difference in pinene content between control and radio frequency treated wood (307 μg/g) is consistent with the average quantity (225 μg/g) of turpentine collected from RFE-1,2,3,4 in Table 23. A better mass balance cannot be achieved because of the high variability. Hence, the quantity of pinene collected corresponds approximately to that lost from the wood. The RF10-31-1A/B entries in Table 23 show that the bulk of the emissions emerge during the first 5 minutes of irradiation. Also, emissions from particle are of the same magnitude as those from the boards.

*Recovery of pinene with steam*

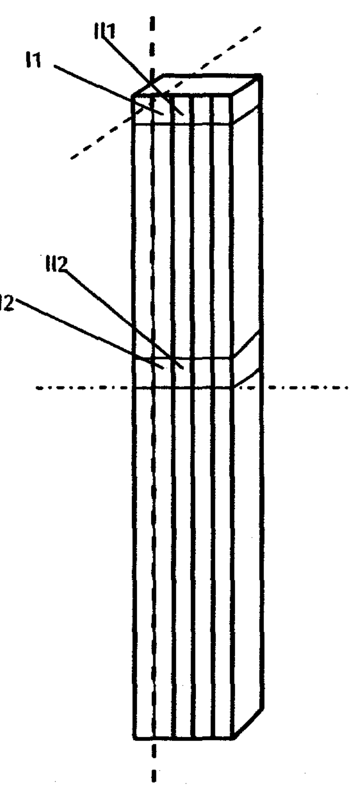


**Figure 10. Location of samples taken from lumber after irradiation.**

One option for recovering the VOCs released from wood during low-headspace RF treatment is by condensing the small amount of steam released. In order to determine the pinene recovered with steam, α-pinene was injected into a 3.5" x 12" polyethylene cylinder containing saturated steam at 100.5°C. The cylinder was then vented to a water-cooled Graham condenser, and the steam collected. No pinene was found (by gc) in the water condensed in the cylinder, indicating that all the pinene was removed by the steam. The recovery data listed in Table 25 show that virtually all the pinene could be recovered when the amount of pinene added is appreciable.

*Diffusion of α-pinene through heartwood and sapwood*

Shavings (10-15 g.) taken from the heartwood and sapwood of a piece of green pine, were Soxhlet-extracted with 150 mL of acetone for 5 hours, with the extracts analyzed for α-pinene by gc. Corresponding samples were dried at 120°C under an airflow of 2.3 lpm, and were similarly extracted. The overall MC of both pieces was 105%. The heartwood MC was 43%; that of sapwood was 121%. The results in Table 26 show that proportionately more pinene is lost from sapwood than from heartwood, reflecting the greater hydrophilicity of the latter. It follows that the turpentine in sapwood will be depleted rapidly, and the heartwood-to-sapwood movement of turpentine will be rate-limiting.

| Table 23: RF treatment of lumber | | |
|---|---|---|
| ID | weight loss (%) | turpentine collected (µg/g, wet basis) |
| RF10-22-1 | 5.4 | 265 |
| RF10-24-1 | 3.4 | 351 |
| RF10-24-2 | 5.3 | 185 |
| RF10-24-3 | 7.7 | 129 |
| RF10-27-1 (RFE-1) | 5.8 | 103 |
| RF10-27-2 (RFE-2) | 4.1 | 159 |
| RF10-29-1 (RFE-3) | 6.9 | 272 |
| RF10-29-2 (RFE-4) | 4.8 | 366 |
| RF10-29-3 (RFSD-01)[1] | 5.4 | 196 |
| RF10-31-1A (first 5 min.) | | 118 |
| RF10-31-1B (next 11 min.) | 5.2 | 65 |
| **average** | **5.4** | **214** |
| | | |
| [1]2,789 g of particle used | | |

| Table 24: FIA emissions of sub-samples from RF-treated lumber (µg/g) | | | | | | |
|---|---|---|---|---|---|---|
| ID | control (no RF) | | I1 | I2 | II1 | II2 |
| total VOCs released during heating at 130°C for 1 hour | | | | | | |
| RFE-1 | 489 | 346 | 307 | 281 | 318 | 256 |
| RFE-2 | 402 | 559 | 154 | 474 | 287 | 528 |
| RFE-3 | 1290 | 445 | 422 | 725 | 441 | 712 |
| RFE-4 | 644 | 1070 | 1360 | 888 | 1210 | 874 |
| average | 700 (σ=300) | | 600 (σ=400) | | | |
| RFSD-01[1] | 740 | | 620 | | | |
| *pinene in acetone extracts* | | | | | | |
| RFE-1 | 1030 | 532 | 472 | 504 | 2320 | 485 |
| RFE-2 | 735 | 570 | 162 | 680 | 268 | 632 |
| RFE-3 | 2720 | 1520 | 588 | 1470 | 1290 | 661 |
| RFE-4 | 1280 | 1710 | 1626 | 1230 | 1810 | 1090 |
| average | 1300 (σ=700) | | 1000 (σ=600) | | | |
| RFSD-01[1] | 1230 | | 720 | | | |
| | | | | | | |
| [1]particle | | | | | | |

| Table 25: Recovery of pinene with steam | | |
|---|---|---|
| ID | pinene added (g.) | recovery (%) |
| STP-1 | 0.85 | 0 |
| STP-2 | 2.57 | 50.2 |
| STP-3 | 12.87 | 92.3 |

| Table 26: Pinene in wood (µg/g.) | | | |
|---|---|---|---|
| | before drying | after drying | percent loss |
| set 1 | | | |
| heartwood | 3910 | 2003 | |
| | 1600 | 554 | |
| | 1230 | 307 | |
| average: | 2250 | 955 | 58 |
| sapwood | 1523 | 316 | |
| | 1092 | 285 | |
| | 2130 | 368 | |
| average: | 1580 | 323 | 80 |
| set 2 | | | |
| heartwood | 1900 | 1141 | |
| | 722 | 624 | |
| | 759 | 294 | |
| average: | 1130 | 686 | 39 |
| sapwood | 549 | 241 | |
| | 572 | 231 | |
| | 539 | 227 | |
| average: | 553 | 233 | 58 |

## *MODELING MOISTURE EMISSIONS FROM WOOD*

Numerous mathematical models exist for moisture emissions from wood. Our model in this report differs from others in the way the wet line and temperature are approached. Moisture, VOC emissions, moisture content, and temperatures at various points are used to develop the differential equations and boundary conditions necessary to get instantaneous emission rates. An activation energy is estimated, and used to model both moisture emission curves at different temperatures, and the internal temperature of the wood. Vectors are normally used to solve instantaneous equations. However, vectors must have the same size in order to be able to perform certain algebraic operations. Since higher temperature runs have shorter vectors than those at lower temperature, equations were developed to achieve the same size vectors. Interpolating functions were used to stretch the smaller vectors, and other equations were developed to reduce the time intervals. Softwood particle was used as the substrate since its nearly spherical shape removes simplifies modeling. OSB flakes were used for measuring the instantaneous surface temperature in a constant temperature furnace. This report describes procedures used to model (a) moisture emissions, at a given furnace temperature, from emissions data obtained at *different* temperatures; (b) temperature based data collected at other temperatures; (c) internal temperature based on moisture emission and surface instantaneous temperature; and VOC emissions from dry particle.

The following assumptions were made for developing a physical model for green particle.

- Free water diffusion occurs while the surface temperature is at or below the boiling point of water.
- Bound water diffuses to the receding wet line above the boiling point of water, and then evaporates.
- Heat diffuses into the wood at a faster rate than water diffuses out. Vapor pressure builds up in the wood interior.

- Steam moves at a faster rate to the surface than the bound water to the wet line.
- The surface temperature of a green flake increases at the same rate as that for green particle.
- The first point of inflection in the moisture emission curve is assumed to be the point at which the free water is depleted, since the moisture content at the moisture peak is at approx. 30% (fsp).

*Governing equations and boundary conditions*

The differential equations used are:

$$-\frac{dC_A}{dt} = k_b C_A \qquad (1)$$

$$\frac{dC_R}{dt} = k_b C_A - k_f C_R \qquad (2)$$

$$\frac{dC_S}{dt} = k_b C_R \qquad (3)$$

Boundary Conditions:

$C_A = C_{Ao}$

$C_R = C_{Ro}$

$C_S = 0$

where

$$C_{Ao} + C_{Ro} = C_A + C_R + C_S \qquad (4)$$

Integration provides both the bound and free water instantaneous emission coefficient rates

$$k_b = \frac{\ln\ (C_{Ro} / C_R)}{t_b} \qquad (5)$$

$$k_f = \frac{\ln\ (1 - (C_S - C_{Ro} / C_{Ao})}{t_f} \qquad (6)$$

C = moisture

k = instantaneous emission coefficient rate

t = time

subscripts:

A = bound water

R = free water

S = surface moisture

o = initial

b = bound (used for coefficient)

f = free

The Arrhenius equation,

$$k_S = Ae^{(-Ea/RTs)} \qquad (7)$$

is then used to solve for the activation energy (Ea) and for the frequency factor (A)

*Model for internal temperature*

The internal temperature can be found for the period of bound water movement by subtracting the logarithmic form of both the surface and internal coefficients. Figure 11 shows the instantaneous temperature profile for the experimental surface, and a model of the internal temperature for the initial period (where the surface temperature is less than the boiling point of water) and free water diffuses to the surface to the point of depletion. The furnace was set at 130°C, and the wood dried for 60 minutes. The green flake surface temperature was used to model the interior temperature, and the sawdust was used to obtain the transport rate coefficients. In later experiments we have measured the internal and surface temperature of wood, which allows us (by using similar equations) to model the emission rate of the bound water. The model below shows that the internal temperature remains cooler for a period of time (temperature below boiling point) and then increases to above the boiling point of water a few minutes after free water depletion.

*Moisture emission curve model at different temperatures*

The activation energy (which was found to be about 9 Kcal/mole) was used to solve for the interpolated coefficient, $k_i$, which was substituted into equation (9). Equation (9) was then interpolated back to the original time interval to get the moisture emission curve model at 160°C from data collected at 130°C.

$$k_i = \exp[-Ea\,(1/T_i - 1/T_2) + \ln k_2] \qquad (8)$$

$$C_{Ri} = C_{Ro}\, e^{-k_i t_i} \qquad (9)$$

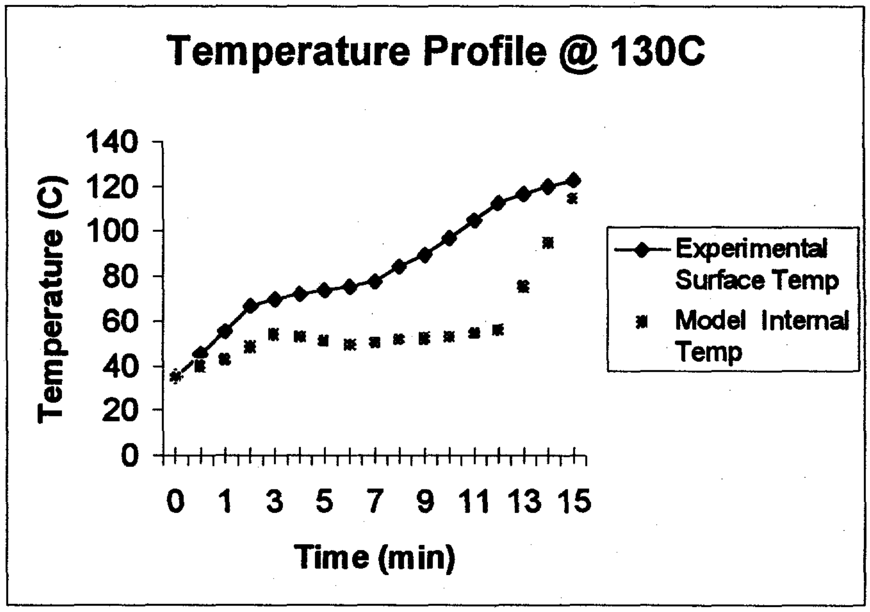


**Figure 11: Model of internal temperature from green flakes' experimental surface temperature during free water diffusion.**

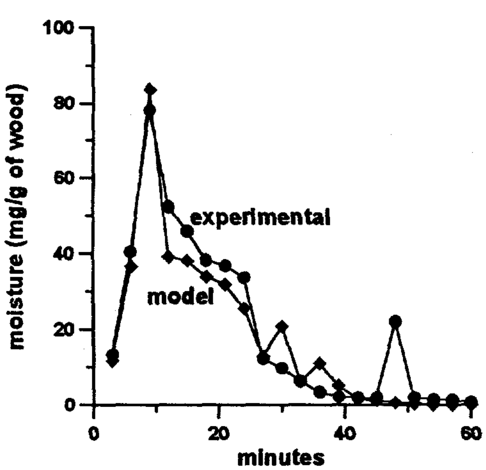


**Figure 12: Comparison of modeled and experimental profiles at 160°C**

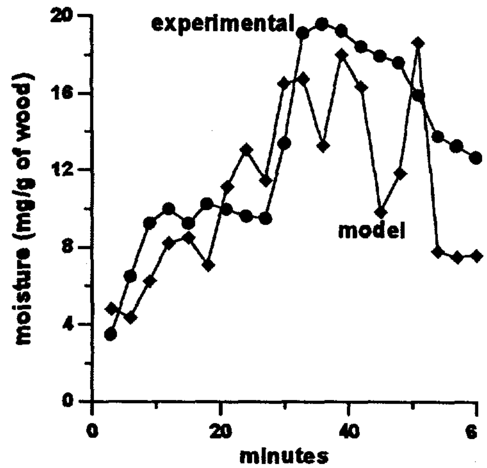


**Figure 13: Comparison of modeled and experimental profiles at 105°C**

The above equations were used only for the first phase (up to free water depletion), in this case for the first 10 minutes. Similar equations were used for the second part of this model. The main differences are the equations used to reduce the time intervals. Figures 12 and 13 compare experimental and the modeled profiles at 160 and 130°C, respectively.

*Moisture profile modeling at 105°C*

Moisture profiles at 105°C were modeled by using: (a) the 105°C instantaneous surface temperature model, and (b) the green particle's moisture model calibrated at 130°C (which was also applied to the above 160°C model). Inevitably the curve of a model which has been made out of two other models will not be as smooth as the curve generated with the experimental data as can be seen in Figure 14. However, the 105°C moisture curve is not as reproducible as the

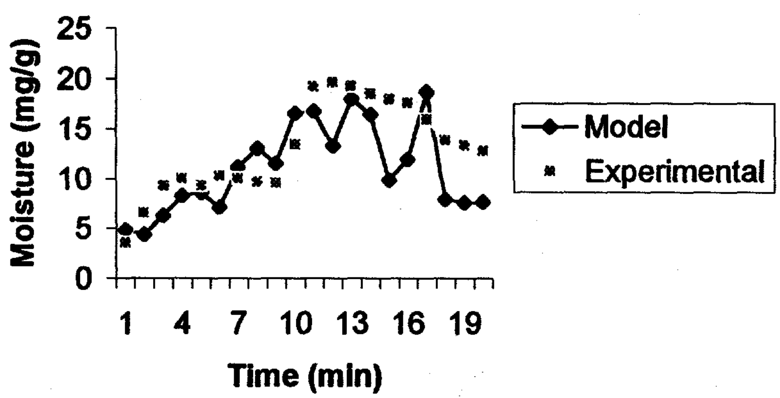


**Figure 14: Comparison of modeled and experimental moisture profile curves at 105°C.**

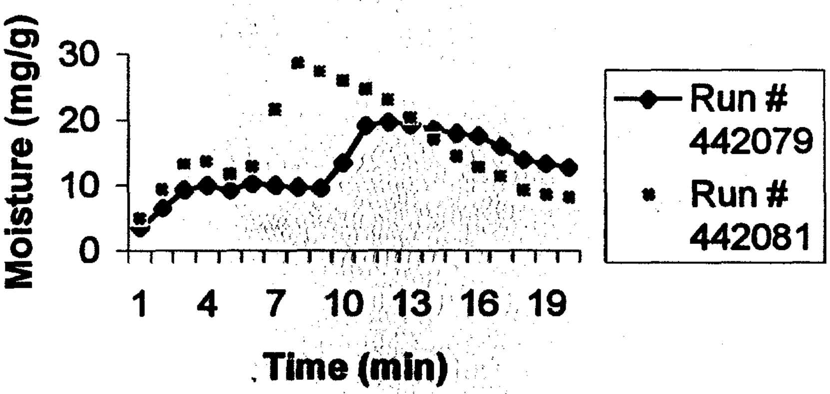


**Figure 15: Comparison of experimental moisture profile curves at 105°C.**

higher temperature curves, as can be seen in Figure 15 where two experimental moisture profiles are compared. Given this variability, the Figure 14 fit is considered to be satisfactory.

*Modeling VOC emissions from dry sawdust*

At 5% moisture, liquid flow is impossible. Below the fiber saturation point, drying is controlled by bound water diffusion and water vapor movement. Temperature gradient, moisture content, time gradient and emission concentrations are taken into consideration for modeling VOC emissions. Softwood particle was dried for 60 minutes to about 5% moisture content, under oven set temperatures of 130C, 160, and 200°C. Both Method 25A emissions and sawdust surface temperatures were measured continuously. The following observations were made.

- The VOC signal is temperature-dependent, increasing in intensity with increasing temperature; the first peak emerges more rapidly with increasing temperature.
- VOC emissions at 130, 160, and 200°C peak when the surface temperature reaches its highest point. In other words, surface temperature and VOC emissions peak simultaneously.
- The initial VOC emissions are directly proportional to the sawdust surface temperature.
- After the initial peak, the VOC emissions decrease gradually while the temperature remains nearly constant.
- More VOC is removed after the initial peak than before the peak at all the temperatures used.
- VOC emissions increase with increasing temperature. Figure 16 shows a break at about 156°C, the boiling point of α-pinene. This suggests that the pinene is not chemically bound to the wood structure or to other species, since otherwise, a higher temperature would be necessary.

The model is based on the following assumptions:

- Particle is spherical.
- At time = 0, there is no VOC on the surface.
- All the VOC is released from below the surface.
- There is still some bound water left.
- Pressure can build up due to evaporation.

A model constructed under the above assumptions at 160°C, is compared to the experimental profile in Figure 17.

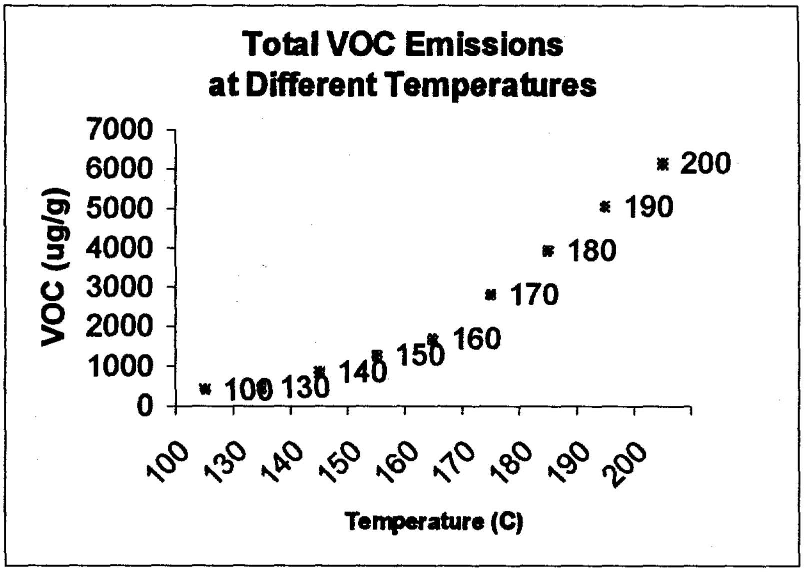


**Figure 16: Sawdust particles at different temperatures.**

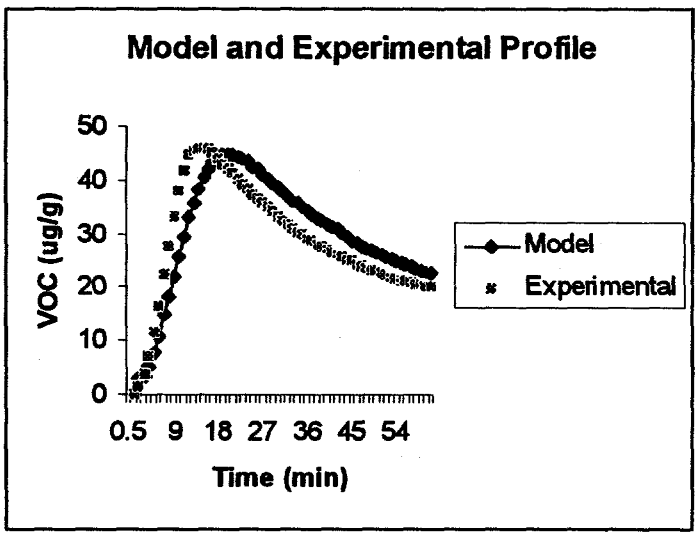


**Figure 17: Comparison of modeled and experimental profiles for VOC emission at 160°C**

These results illustrate that our basic assumptions are correct. We will now extend them to moisture and VOC release under low headspace conditions.

***SMALL SCALE PILOT WORK***

The pilot unit illustrated in Figure 18 has been loaned to us by American Kiln. It has a volume of 1,000 liters, and is powered by a 5 kW generator. Wood will be placed between the two electrodes, and will occupy roughly half of the available volume, so as to maintain a low headspace. The unit is sealed, and has two ports, one of which will be used to remove and condense the small amount of steam generated, and recover the turpentine. Periodic delivery

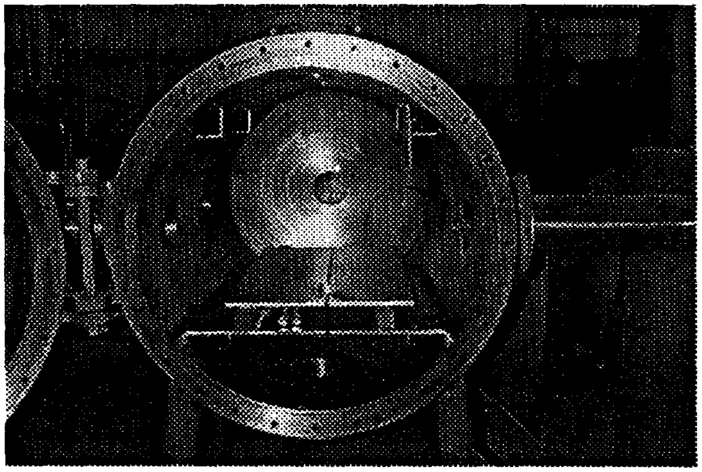

**Figure 18: Photograph of the pilot RF unit**

of lumber has been scheduled from Georgia-Pacific's Warrenton, GA facility, and preliminary work has already begun.

### *DEPENDENCE OF VOC EMISSIONS ON DRYING PRACTICES*

#### *Kiln modifications*

ADAM® analog/digital (A/D) and digital/analog (D/A) converters were interfaced to a PC through the serial input/output (I/O) port for monitoring temperatures and load cell readings. The additional temperature data acquisition capability allowed the monitoring and improved control of the wet-bulb/dry-bulb temperatures and the rate of drying throughout the run. The wet-bulb temperature was computer-controlled by increasing or decreasing the airflow with a reference voltage applied with the D/A converter. A separate temperature controller was used to ramp up the dry-bulb temperature at a rate that approximates the heating time of a full-size kiln. A shroud around the circulation fan was modified to increase the maximum flow rate through the stack of lumber samples. The fan is controlled by a variable-speed DC motor, and an airflow rate of up to 1500 feet per minute can be achieved.

#### *Temperature dependence of the drying profile*

One kiln charge was dried to determine if the first and second peaks in VOC emissions were associated with either a change in drying rate or a change in the internal or surface temperature of the lumber samples. Load cells were used to monitor the weight loss, or the rate of drying. One thermocouple was positioned at the center of one lumber sample and a second thermocouple was positioned 2 mm below the surface. Target dry-bulb and wet-bulb temperatures were 240 and 180°F, respectively.

The maximum VOC emission rate occurred at approximately 1 hour into the drying cycle with a sample surface temperature in the range of 60 to 70°C (140 to 158°F). As drying continued and moisture content approached 30%, the surface temperature increased. At this point the VOC emission rate also increased. The increase in wood temperature at the lower moisture probably accounts for the second increase in VOC emissions that had been observed in previous drying experiments with lumber and also with OSB and particle (IPST results). Actual measurements for this experiment are shown in Table 27.

*VOC reduction through delayed venting*

Three kiln charges of lumber samples were dried to determine if delayed venting would reduce VOC emissions. Each kiln charge consisted of fifteen matched 2" x 6" rough sawn green southern pine lumber samples 23" in length. The temperature was ramped from ambient to 240°F over a two-hour time period. Venting and wet bulb controls were initiated after 2, 3, and 5 hours for the three different kiln charges.

**Table 27: VOC emissions, surface temperature and weight of wood for one kiln charge of Southern pine lumber samples.**

| time (hours) | VOC ppm 10E-1 | wood surface temperature, °C | MC % | weight (lbs.) |
|---|---|---|---|---|
| 0.0 | 2.07 | 10.7 | 71.5 | 82.5 |
| 0.5 | 23.90 | 43.5 | 71.0 | 82.2 |
| 1.0 | 58.40 | 63.1 | 68.8 | 81.2 |
| 1.5 | 33.30 | 72.1 | 66.1 | 79.9 |
| 2.0 | 20.80 | 76.4 | 62.8 | 78.3 |
| 2.5 | 5.80 | 78.8 | 61.1 | 77.5 |
| 3.0 | 11.80 | 79.8 | 85.4 | 76.2 |
| 3.5 | 9.40 | 80.6 | 56.8 | 75.4 |
| 4.0 | 7.80 | 80.9 | 54.1 | 74.1 |
| 4.5 | 6.70 | 81.1 | 52.4 | 73.3 |
| 5.0 | 6.00 | 81.2 | 49.7 | 72.0 |
| 5.5 | 5.60 | 81.3 | 47.0 | 70.7 |
| 6.0 | 5.40 | 81.9 | 44.2 | 69.4 |
| 6.5 | 5.50 | 82.1 | 42.0 | 68.3 |
| 7.0 | 5.00 | 82.1 | 38.2 | 66.5 |
| 7.5 | 5.10 | 83.2 | 35.5 | 65.2 |
| 8.0 | 5.40 | 82.7 | 32.8 | 63.9 |
| 8.5 | 5.90 | 83.0 | 29.5 | 62.3 |
| 9.0 | 6.70 | 83.5 | 25.7 | 60.5 |
| 9.5 | 7.50 | 84.1 | 22.4 | 58.9 |
| 10.0 | 7.70 | 85.0 | 19.7 | 57.6 |
| 10.5 | 8.50 | 86.3 | 16.4 | 56.0 |
| 11.0 | 9.30 | 87.9 | 14.6 | 55.1 |
| 11.5 | 9.60 | 89.6 | 12.3 | 54.0 |

| Table 28: Effect of delayed venting on VOC release | | | |
|---|---|---|---|
| charge # | green weight (lbs) | dry weight (lbs) | VOCs (lbs/dry ton) |
| 1 (no vent 2 hrs) | 128 | 63 | 3.05 |
| 2 (no vent 3 hrs) | 131 | 65 | 2.47 |
| 3 (no vent 5 hrs) | 129 | 64 | 1.89 |

During heating with no initial venting for 2, 3 and 5 hours the VOC emissions (Table 28) were 3.05, 2.47, and 1.89 lbs/dry ton, respectively. A small amount of steam was observed at the sample outlet of the kiln after about 3 hours. The amount of VOC emissions that occurred during this time period was not measurable and the weight loss indicated that the volume of water vapor was extremely small. Since the airflow was kept at zero, the wet-bulb and dry-bulb temperatures remained the same and no appreciable drying occurred during this time.

After the initial heating period the wet bulb was controlled at 180°F with the D/A signal to the Hastings airflow controller. Each charge was dried for a total of 18 hours to give a final moisture content of approximately 6 percent. This procedure substantially reduced VOC emissions. These results are a larger-scale validation of the conclusions arrived at earlier for steaming smaller pieces of wood.

### *VARIATION OF MONOTERPENES IN LOBLOLLY PINE*

#### *Seasonal effects*

This section describes a continuation of an experiment begun in March, 1997, to determine if there are seasonally-related variations in volatile organic emissions from wood harvested from southern pine trees. The same twelve loblolly pines (*Pinus taeda*) standing in the Mississippi State University Starr Memorial Forest have been sampled via increment core collection of samples since last October, and twelve trees in close proximity to this stand were sampled for the six months previous. All the trees are about 40 – 45 years old and have an approximate diameter of 14+ inches (35 cm). The increment cores were collected at a height of approximately 42 inches using a 12-inch long increment borer with a core diameter of 0.2 inches. Following each removal of an increment core, wooden dowels have been placed in the resulting cavity to decrease tree damage during the projected twelve months of sampling. After removal from the tree the cores are always divided into three sections, with the innermost section (closest to the pith) being designated as the "inside" sample, the second as the "middle" sample and the outermost (adjacent to the bark) being designated as the "outside" sample. Samples are placed in preweighed test tubes and returned to the laboratory for monoterpene analysis using gas chromatography.

Core samples for gas chromatographic analysis are prepared by adding 10 mL of methylene chloride and a 1,4-dichlorobenzene internal standard to each sample in a closed test tube. Samples are then sonically agitated for 1 hour, the appropriate amount of diphenylmethane (internal standard) added, and concentrated in a hot water bath to 5 ml for inside samples and 1 ml for middle and outside samples. A 1 ml sample is taken from each concentrate for analysis and 0.1 ml of ether diazomethane is added to derivatize the sample for analysis on a Varian 3600 gas chromatograph equipped with a J&W DB-5 30 meter capillary column and flame ionization detector. Target monoterpene compounds are α-pinene, camphene, β-pinene, limonene, fenchyl alcohol, borneol, 4-allylanisole, and methyl eugenol; the gas chromatograph also analyzes the sonicated extract for the diterpene compounds (*i.e.*, resin acids) pimaric acid, isopimaric acid, levopimaric acid, dehydroabietic acid, abietic acid, and neoabietic acid. Increment cores are dried in an analytical oven overnight to obtain the dry weight of the wood. The dry increment core weight (grams) and the amount of each individual compound (expressed as grams of compound) are used to calculate the percentage of each compound using this equation:

$$\frac{\text{Amount of Individual Compound}}{\text{Dry Weight of Sample}} x\ 100\% = \text{Total Percentage of Compound}$$

The results of the monoterpene analyses for the samples taken in March, 1997 through June 1998 accompany this report in Appendix 1. Figures 17-19 represent the α-pinene data from Appendix 1; box and whisker plots for the minima, maxima, and the $25^{th}$ and the $75^{th}$ percentile points. Alpha-pinene was chosen to represent VOC trends as it comprises about 70% of the VOCs present in southern pine. Essentially, these charts show that there is little evidence for variation in α-pinene content based upon the analysis of the March 1997 – June 1998 increment cores.

As this is a longitudinal study, the variation of α-pinene can also be charted by month to see if individual trees follow the identical trends. Figure 20 represents data from the *innermost* cores for four out of the possible twelve samples, indicates that some trees follow the same pattern of concentration changes as their brethren, while other trees act in exactly the opposite fashion. For example, note how tree #3 acts contrary to the others during the summer months of 1997 and 1998. It is difficult to determine from this sampling whether there are seasonal trends for inside core samples.

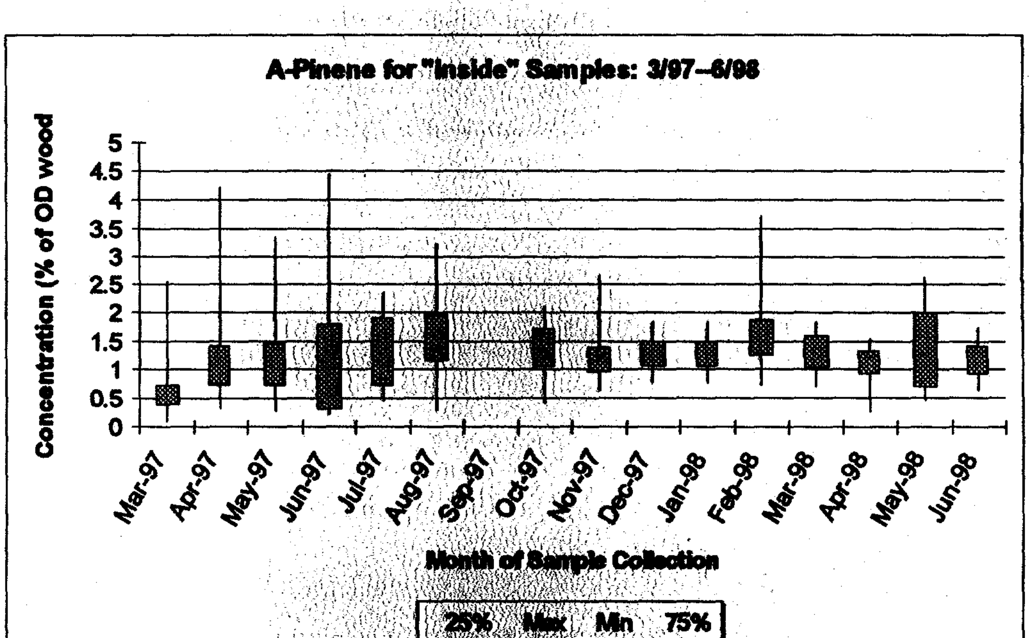


**Figure 17: α-Pinene for "inside" samples (397-698)**

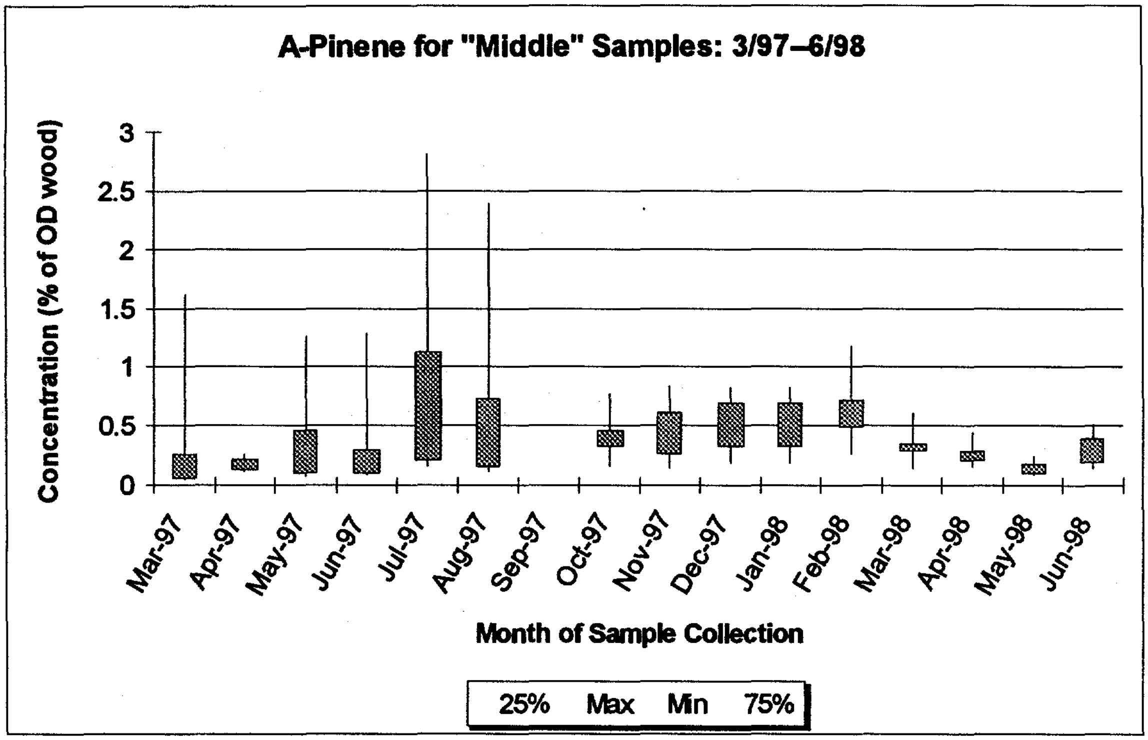


**Figure 18: α-Pinene for "middle" samples (397-698)**

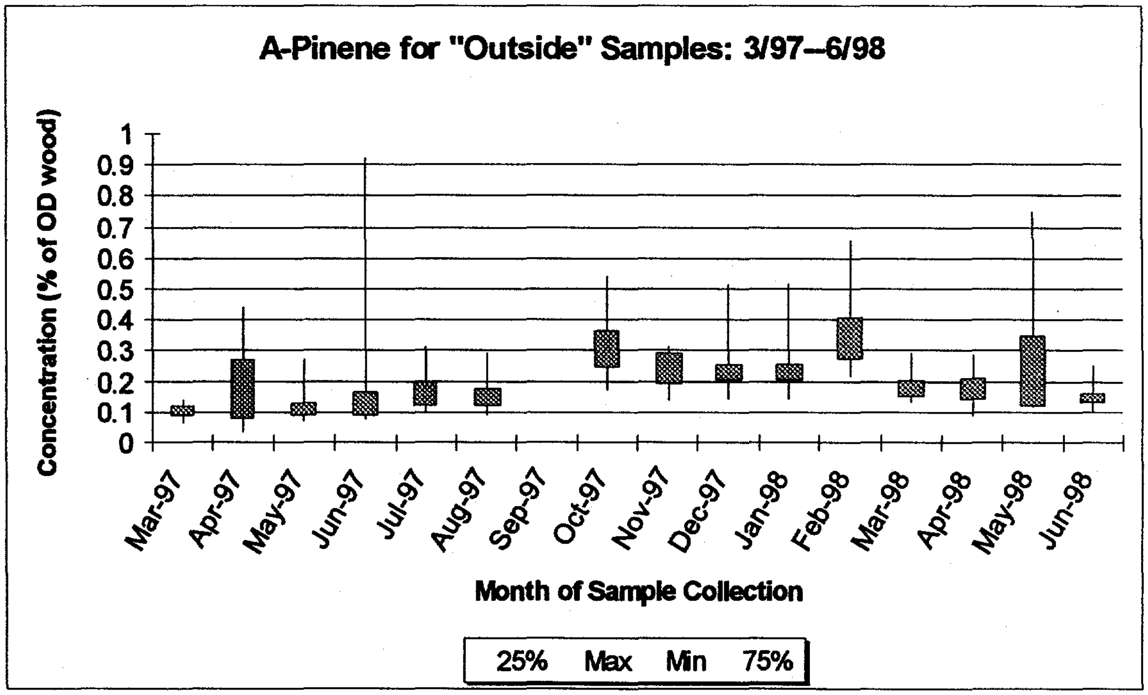


**Figure 19: α-Pinene for "outside" samples (397-698)**

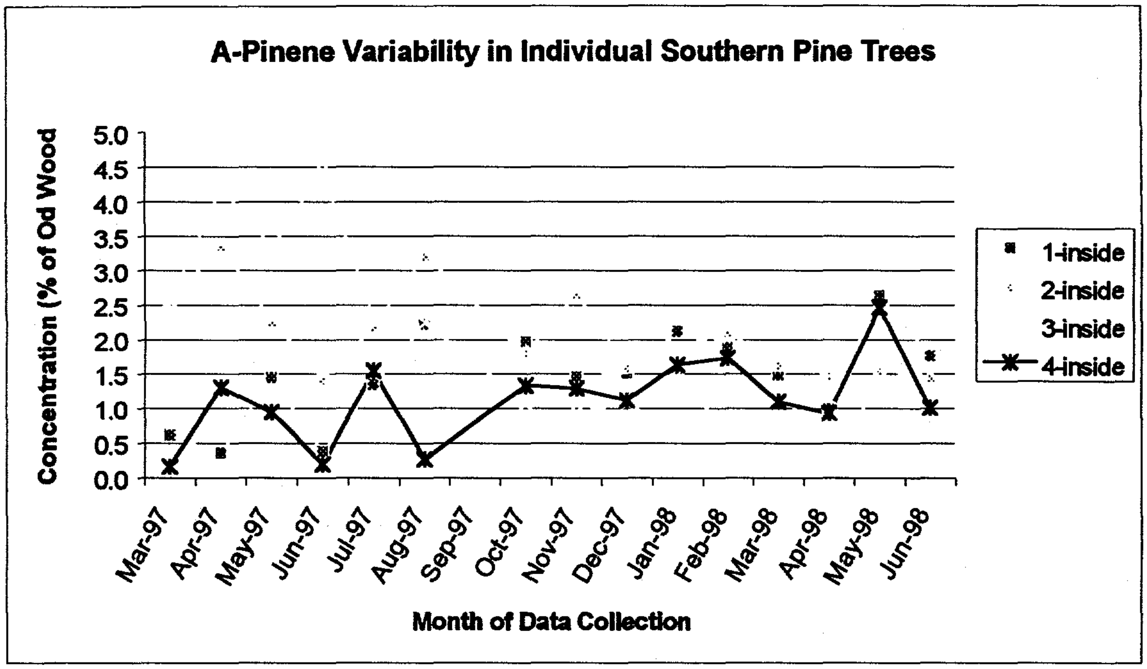


**Figure 20: α-Pinene variability in individual Southern pine trees (innermost cores)**

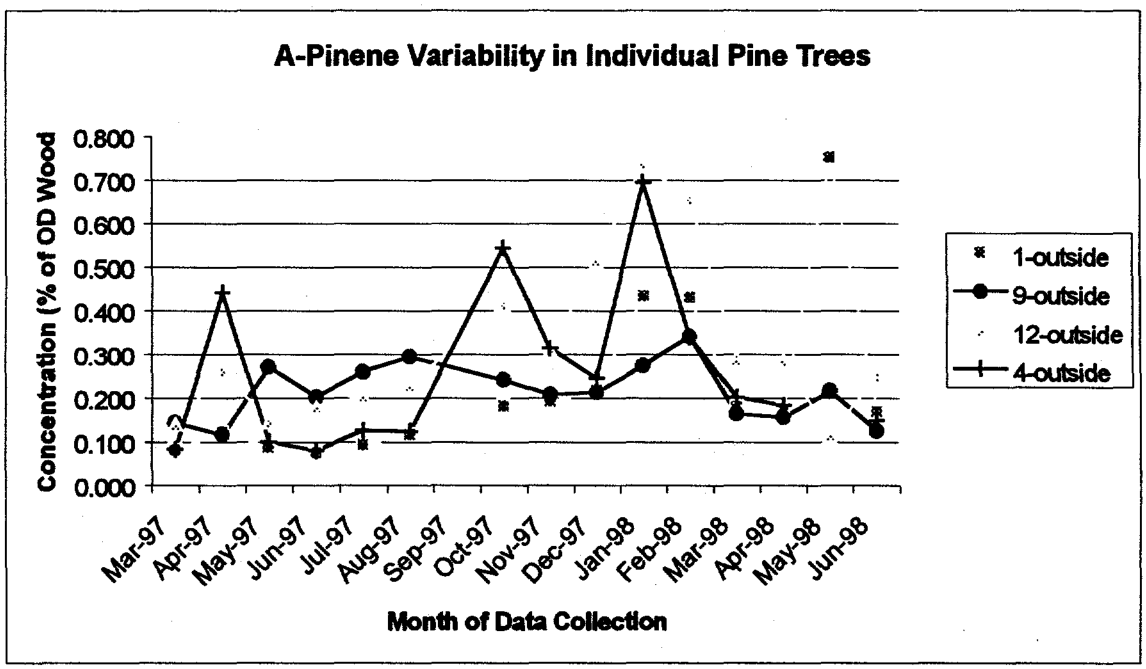


**Figure 21: α-Pinene variability in individual Southern pine trees (outside cores)**

Figure 21 charts the *outside* core data; due to missing values for May 1998, some different trees were included to represent the data trends. Tree #4, while missing data for May, was included purposely because of its wide-ranging concentration values. Once again some contrariness is noted (e.g., tree #1 during certain months), but all-in-all there appear to be similar trends for the different trees plotted here. In spite of the fact that the trends are similar, though, by comparing tree #9 with trees #4 and #12 it is apparent that there are great differences in the degree to which α-pinene concentrations vary with seasonal factors. As these trees are all maintained in the same sample plot in one plantation, it seems appropriate to conclude that there may be a genetically-based response to seasonal stimuli.

*VOC emissions from samples taken from different locations within the bole of the tree*

Due to the variability of the monoterpene content within the sample trees at breast height, it was desired to conduct a simple experiment to determine whether this variability (and the monoterpene concentrations) varied with height. One loblolly pine approximately 45 years old (located near the other twelve sample trees) was selected for this experiment. Core samples were collected at approximately 3, 10, 20, and 30 feet from ground level (4 cores). The concentrations of monoterpenes and resin acids were first determined in the outside, middle, and inside portions of each core as previously described. The results are shown in Table 29. Figure 22 illustrates values for the concentration of α-pinene (the predominant VOC) at varying heights in the selected loblolly pine tree, expressed as a percent of the cores' oven-dry weights. The concentration of α-pinene did not greatly depend upon the height at which the sample was taken (at least, at this point in the sampling cycle). As expected, the concentrations of the innermost samples were several times that of the center core section, and the outermost section concentration was significantly lower (as expected from other collected data). With the exception of the outermost section's somewhat higher concentration of α-pinene at the lowest sampling point (3 feet), all of the concentrations were about the same from one height to the next. Thus far we have not located other documentation to substantiate these monoterpene measurements in trees at differing heights (with the exception of measurements on twigs and needles), although stories of such proprietary studies persist in the oral wood products industry tradition.

**Table 29: Harvested tree increment core data (g/g OD wood %) for April 1998**

| height | α-pinene | camphene | β-pinene | myrcene | limonene | fenchyl alcohol | borneol | 4-allyl-anisole | total |
|---|---|---|---|---|---|---|---|---|---|
| 1 m-inside | 0.711 | 0.026 | 0.080 | 0.037 | 0.117 | 0.020 | 0.020 | 0.021 | 1.031 |
| -middle | 0.203 | 0.004 | 0.050 | 0.072 | 0.037 | 0.001 | 0.001 | 0.008 | 0.375 |
| -outside | 0.225 | 0.003 | 0.021 | 0.005 | 0.012 | 0.000 | 0.000 | 0.010 | 0.276 |
| 3 m-inside | 0.787 | 0.020 | 0.170 | 0.020 | 0.117 | 0.014 | 0.003 | 0.101 | 1.233 |
| -middle | 0.157 | 0.002 | 0.051 | 0.004 | 0.020 | 0.000 | 0.000 | 0.004 | 0.237 |
| -outside | 0.036 | 0.000 | 0.008 | 0.001 | 0.003 | 0.000 | 0.000 | 0.002 | 0.051 |
| 6 m-inside | 0.702 | 0.016 | 0.151 | 0.014 | 0.100 | 0.010 | 0.001 | 0.087 | 1.080 |
| -middle | 0.174 | 0.002 | 0.051 | 0.049 | 0.003 | 0.000 | 0.000 | 0.003 | 0.282 |
| -outside | 0.041 | 0.001 | 0.009 | 0.001 | 0.003 | 0.000 | 0.000 | 0.002 | 0.057 |
| 9 m-inside | 0.717 | 0.014 | 0.147 | 0.012 | 0.095 | 0.009 | 0.001 | 0.092 | 1.087 |
| -middle | 0.152 | 0.001 | 0.048 | 0.051 | 0.003 | 0.000 | 0.000 | 0.002 | 0.257 |
| -outside | 0.042 | 0.001 | 0.008 | 0.001 | 0.003 | 0.000 | 0.000 | 0.002 | 0.057 |

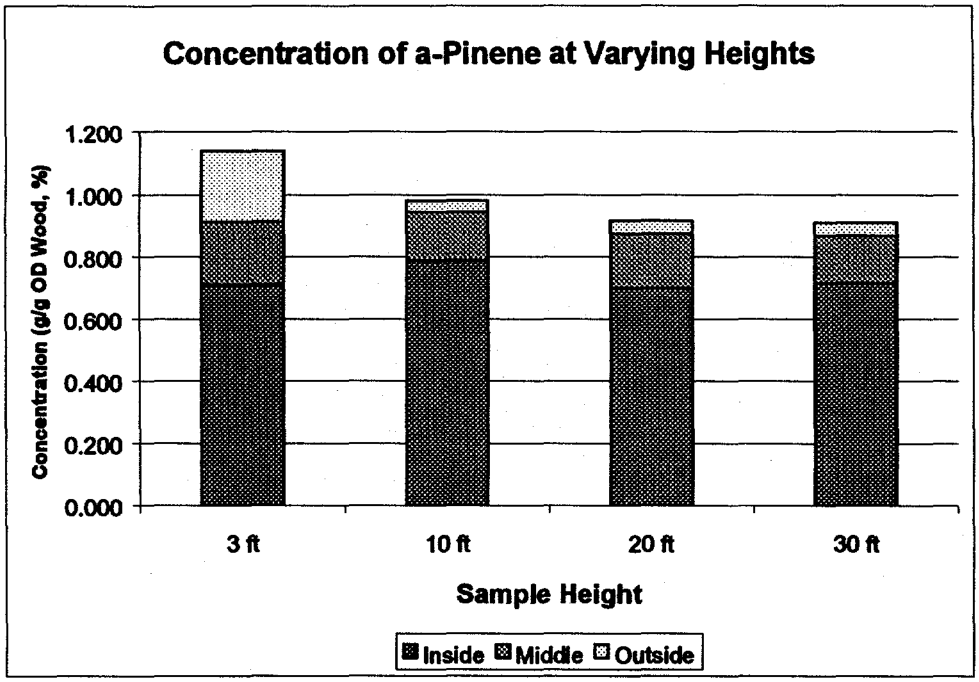


**Figure 22: Concentration of α-pinene at various tree heights**

The tree was harvested and sawn into three eight-foot logs to provide twelve pilot scale kiln charges from heartwood and sapwood regions at different heights of the tree. The samples for each of the two kiln charges from each log were randomly selected from all of the appropriate boards from each log. VOC emissions from the exhaust stream of the dry kiln were determined with the Total Hydrocarbon Analyzer for each set of samples using a high temperature drying schedule for all experiments. The results are illustrated in Figure 23. These data are intriguing because they appear to show that the concentration of VOCs was significantly higher for heartwood samples taken from the uppermost log, but this trend was not expected based upon the increment core analyses. Investigation of possible reasons for the discrepancy between these results has recently begun. The boards selected for drying contained very few knots, so the hypothesis that the increment cores collected from this top log did not adequately sample the greater percentage of knotty wood (containing a greater percentage of volatile compounds) that should be expected from this region of the tree is probably untenable.

***STATISTICAL CORRELATIONS OF VOC DATA***

Data on the seasonal dependence of VOC emissions collected from 3.97-2.98 were analyzed by the SAS statistical package. While interpretation of the data is incomplete, some of the trends identified are as follows. The analysis was restricted to linear effects, and only correlations significant at 90% or better are reported. For example, the first item in the data indicates that the only coefficient of variance, CoV, (and not the absolute amount of dehydrobietic acid) correlated with the average temperature.

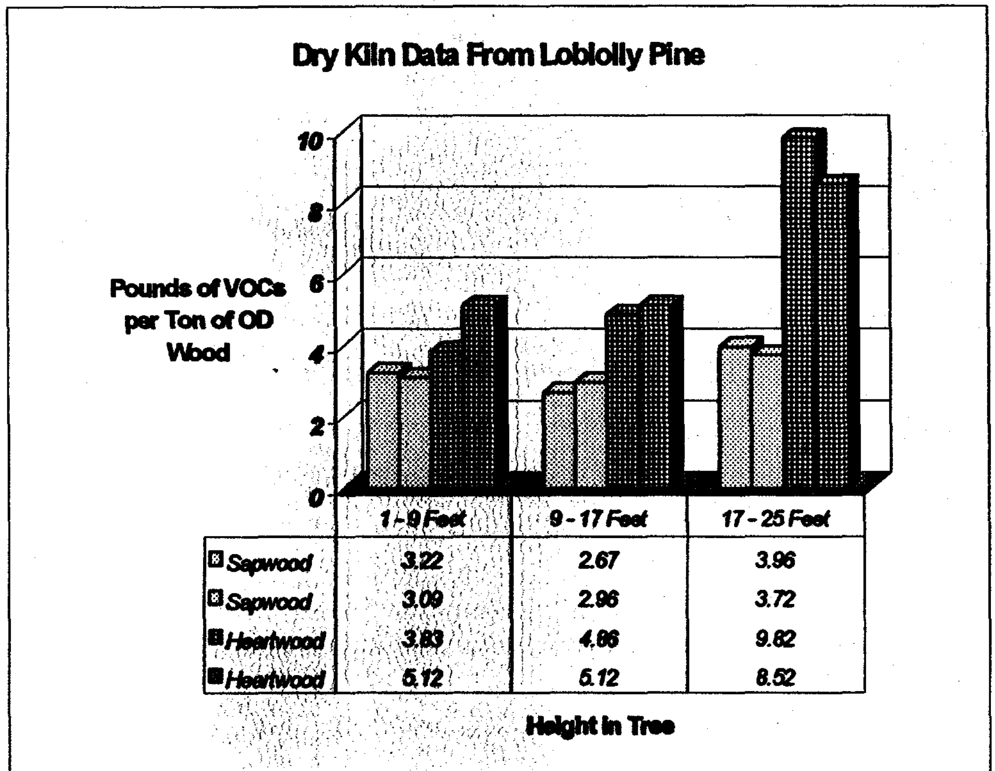


**Figure 23: Dry kiln data from loblolly pine.**

*Correlative Associations with the Average Temperature*
Dehydroabietic Acid: CoV
Abietic Acid: CoV
Neoabietic Acid: Std. Deviation, Variation, Range, CoV
Total Resins: CoV

*Correlative Associations with the Total Rainfall/Average Rainfall*
Alpha-Pinene: Std. Deviation, Range
Dehydroabietic Acid: Range, Mean, Std. Deviation (Total rain only)
Abietic Acid: Mean, Std. Deviation, Variance, Range
Neoabietic Acid: Mean
Total Monoterpenes: Mean, Variance, Range
Total Resin Acids: Mean, Variance, Range
Combined Monoterpenes and Resin Acids: Mean, Range

*Correlative Associations with the Total Sunlight/Average Sunlight*
Alpha-Pinene: Std. Deviation, Variance, Range
Camphene: Negative Mean, CoV
Beta-Pinene: Negative Mean, CoV
Limonene: Negative Mean, Negative Std. Deviation, Negative Range
Fenchyl Alcohol: Negative Mean, Negative Std. Deviation, Negative Variance, Negative Range
Borneol: Negative Mean, Negative Std. Deviation, Negative Range, CoV

Dehydroabietic Acid: Mean, Std. Deviation, Variance, Range
Abietic Acid: Std. Deviation, Range
Neoabietic Acid: Std. Deviation, Variance, Range, CoV
Total Monoterpenes: Negative Monoterpene Totals, CoV
Total Resin Acids: Mean, Variance, Range, CoV
Combined Monoterpenes and Resin Acids: Mean, Variance, CoV

These correlations will be refined and interpreted after data collection is complete.

In conclusion, the increment core data collected and analyzed as lumped data for VOC content since March of 1997 appear to show that the VOC content of loblolly pine trees does not significantly vary with the season. This method of analysis may obscure real trends due to contrary behavior of a portion of the sample population. It is possible that there is a genetically-based response that has not been accounted for. In addition, there is conflicting information about the VOC content as a function of height. VOC emissions collected during a dry kiln study of mostly clear wood appear to indicate that there is a significantly greater VOC emission for wood (especially heartwood) gathered near the top of the tree, while increment core studies appear to indicate that the VOC content is essentially constant regardless of height.

*MECHANISM OF MICROWAVE (OR RF-INDUCED) VOC RELEASE*

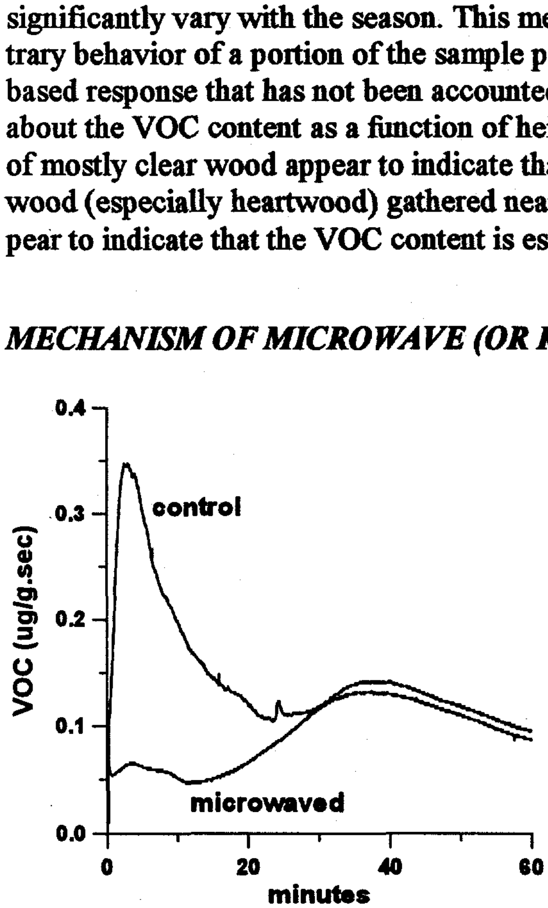


**Figure 24: VOC profiles from control and microwaved OSB flakes**

The VOCs lost from wood maintained under low-headspace conditions under a microwave field originate from the periphery of the furnish. Consider the profiles in Figure 24 which are VOC profiles from drying control and microwaved (low-headspace) OSB flakes. The data were collected as a part of our companion EPRI project on wood drying. Note that the reduction in VOCs for the microwaved wood occurs early in the process. The initial VOC peak reflects surficial material, which is released when the wood is initially heated (9). The second broader band arises when the wood is largely dry, and originates from the interior of the furnish. The wood dries in approximately 25 minutes in the Figure 24 experiment, i.e. during the rise of the second peak. Since microwaving affects this second signal minimally, if at all, it is clear that only the surface VOCs are released during drying. Much of the mass in a piece of wood resides near the surface. For example, consider a cube of length $l$. Its volume is then $l^3$. The volume of wood lying within a distance of $0.1l$ of the surface is $0.49l^3$. Hence, these experiments demonstrate that only the surface VOCs are lost during microwaving.

Energy transferred to water constrained in wood is probably dissipated by increased thermal motion of the water within the wood matrix. The isotopic work discussed earlier illustrates this quite well; under irradiation, $D_2O$ is able to access hydrogen-bonded areas that are otherwise excluded. Thus, there must be at least two means of VOC removal from wood during conventional drying. Water must be at least partially responsible for VOC loss from green wood during early drying, whereas VOC removal from dry wood is driven by vapor pressure considerations (9, 10).

The VOC material is concentrated in hydrophobic regions within the wood matrix. We believe that transferring energy to water while constraining it to remain in the wood promotes transport of the VOCs to hydrophilic zones. Alexiou et al (11) have shown that pre-steaming *Eucalyptus* mobilizes heartwood extractives, probably by allowing water greater access to cell walls. Irradiating the wood under low-headspace conditions appears to promote this access. The air:water dimensionless Henry's Law Constant, the distribution coefficient between the two media, is estimated to be 4.38 at room temperature (15). It is likely to be much higher at 95°C, since the vapor pressure rises much more quickly with increasing temperature (12) than does solubility (13). Also, the sapwood is likely to heat up more rapidly than heartwood during microwaving/RF owing to its higher water content, and the resulting temperature and pressure gradients may promote mixing.

Details of the physics of VOC removal are not presently known, and are currently under study. However, the only apparent difference between VOC extraction through steaming and microwaving/RF, is that the latter occurs much more quickly. Since water absorbs microwave much more easily than does wood, the wood is principally heated by the water, and the wood-water interaction should, therefore, be more closely coupled in microwaving/RF, than during steaming. This, in turn, should transfer more VOC material into the aqueous phase, and thence to the atmosphere.

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## APPENDIX 1

Monoterpenes from Southern Yellow Pine Loblolly increment cores
(March 1997 – June 1998)

**Monoterpenes from SYP (loblolly) increment cores: March, 1997**

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 0.601 | 0.013 | 0.290 | 0.053 | 0.035 | 0.007 | 0.009 | 0.061 | 1.069 |
| 1-middle | 0.744 | 0.023 | 0.398 | 0.061 | 0.001 | 0.006 | 0.000 | 0.046 | 1.279 |
| 1-outside | 0.082 | 0.001 | 0.067 | 0.010 | 0.003 | 0.000 | 0.000 | 0.021 | 0.182 |
| 2-inside | 2.560 | 0.046 | 0.187 | 0.104 | 0.028 | 0.000 | 0.000 | 0.080 | 3.005 |
| 2-middle | 0.138 | 0.002 | 0.008 | 0.005 | 0.001 | 0.000 | 0.000 | 0.008 | 0.161 |
| 2-outside | 0.119 | 0.001 | 0.006 | 0.005 | 0.001 | 0.000 | 0.000 | 0.006 | 0.138 |
| 3-inside | 2.560 | 0.046 | 0.187 | 0.104 | 0.028 | 0.000 | 0.000 | 0.080 | 3.005 |
| 3-middle | 0.073 | 0.001 | 0.014 | 0.002 | 0.006 | 0.000 | 0.000 | 0.006 | 0.102 |
| 3-outside | 0.064 | 0.001 | 0.010 | 0.002 | 0.001 | 0.000 | 0.000 | 0.010 | 0.088 |
| 4-inside | 0.161 | 0.003 | 0.028 | 0.005 | 0.014 | 0.002 | 0.003 | 0.008 | 0.224 |
| 4-middle | 0.346 | 0.006 | 0.143 | 0.028 | 0.022 | 0.000 | 0.000 | 0.016 | 0.562 |
| 4-outside | 0.083 | 0.001 | 0.037 | 0.006 | 0.004 | 0.000 | 0.000 | 0.014 | 0.145 |
| 5-inside | 0.487 | 0.007 | 0.059 | 0.023 | 0.010 | 0.002 | 0.002 | 0.007 | 0.595 |
| 5-middle | 0.059 | 0.001 | 0.009 | 0.004 | 0.000 | 0.000 | 0.000 | 0.001 | 0.074 |
| 5-outside | 0.122 | 0.001 | 0.013 | 0.007 | 0.001 | 0.000 | 0.000 | 0.005 | 0.149 |
| 6-inside | 0.363 | 0.012 | 0.172 | 0.006 | 0.039 | 0.009 | 0.011 | 0.009 | 0.622 |
| 6-middle | 0.082 | 0.001 | 0.085 | 0.002 | 0.007 | 0.000 | 0.000 | 0.004 | 0.181 |
| 6-outside | 0.085 | 0.001 | 0.066 | 0.002 | 0.005 | 0.000 | 0.000 | 0.007 | 0.166 |
| 7-inside | 0.465 | 0.006 | 0.058 | 0.015 | 0.000 | 0.000 | 0.000 | 0.006 | 0.550 |
| 7-middle | 0.057 | 0.000 | 0.009 | 0.002 | 0.003 | 0.000 | 0.000 | 0.001 | 0.072 |
| 7-outside | 0.114 | 0.001 | 0.018 | 0.004 | 0.006 | 0.000 | 0.000 | 0.005 | 0.149 |
| 8-inside | 0.381 | 0.003 | 0.091 | 0.002 | 0.006 | 0.000 | 0.000 | 0.006 | 0.488 |
| 8-middle | 0.080 | 0.001 | 0.040 | 0.001 | 0.002 | 0.000 | 0.000 | 0.005 | 0.129 |
| 8-outside | 0.068 | 0.001 | 0.031 | 0.001 | 0.002 | 0.000 | 0.000 | 0.007 | 0.108 |
| 9-inside | 0.290 | 0.008 | 0.082 | 0.002 | 0.031 | 0.008 | 0.009 | 0.070 | 0.500 |
| 9-middle | 0.235 | 0.005 | 0.145 | 0.004 | 0.026 | 0.002 | 0.002 | 0.006 | 0.425 |
| 9-outside | 0.142 | 0.002 | 0.097 | 0.004 | 0.013 | 0.000 | 0.000 | 0.003 | 0.261 |
| 10-inside | 0.392 | 0.006 | 0.051 | 0.005 | 0.052 | 0.001 | 0.002 | 0.002 | 0.511 |
| 10-middle | 0.051 | 0.000 | 0.013 | 0.001 | 0.007 | 0.000 | 0.000 | 0.001 | 0.074 |
| 10-outside | 0.086 | 0.001 | 0.023 | 0.002 | 0.011 | 0.000 | 0.000 | 0.009 | 0.131 |
| 11-inside | 0.085 | 0.000 | 0.045 | 0.001 | 0.002 | 0.000 | 0.000 | 0.000 | 0.132 |
| 11-middle | 0.040 | 0.000 | 0.020 | 0.001 | 0.001 | 0.000 | 0.000 | 0.001 | 0.064 |
| 12-inside | 1.075 | 0.020 | 0.300 | 0.022 | 0.037 | 0.004 | 0.007 | 0.020 | 1.486 |
| 12-middle | 1.617 | 0.049 | 0.345 | 0.037 | 0.099 | 0.019 | 0.025 | 0.022 | 2.214 |
| 12-outside | 0.140 | 0.002 | 0.046 | 0.003 | 0.003 | 0.000 | 0.000 | 0.012 | 0.207 |

**Monoterpenes from SYP (loblolly) increment cores: April, 1997**

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 0.351 | 0.004 | 0.224 | 0.028 | 0.010 | 0.000 | 0.000 | 0.031 | 0.649 |
| 1-middle | 0.148 | 0.002 | 0.122 | 0.016 | 0.005 | 0.000 | 0.000 | 0.022 | 0.316 |
| 1-outside | 0.121 | 0.002 | 0.098 | 0.014 | 0.005 | 0.000 | 0.000 | 0.029 | 0.270 |
| 2-inside | 3.361 | 0.055 | 0.232 | 0.126 | 0.039 | 0.000 | 0.000 | 0.162 | 3.975 |
| 2-middle | 0.158 | 0.002 | 0.009 | 0.006 | 0.002 | 0.000 | 0.000 | 0.009 | 0.186 |
| 2-outside | 0.086 | 0.001 | 0.020 | 0.002 | 0.001 | 0.000 | 0.000 | 0.002 | 0.112 |
| 3-inside | 4.220 | 0.066 | 0.968 | 0.150 | 0.071 | 0.000 | 0.000 | 0.213 | 5.687 |
| 3-middle | 0.103 | 0.001 | 0.022 | 0.004 | 0.003 | 0.000 | 0.000 | 0.027 | 0.158 |
| 3-outside | 0.182 | 0.003 | 0.034 | 0.007 | 0.010 | 0.001 | 0.001 | 0.004 | 0.242 |
| 4-inside | 1.302 | 0.018 | 0.505 | 0.092 | 0.081 | 0.000 | 0.000 | 0.116 | 2.113 |
| 4-middle | 0.122 | 0.002 | 0.047 | 0.008 | 0.007 | 0.000 | 0.000 | 0.031 | 0.217 |
| 4-outside | 0.441 | 0.008 | 0.044 | 0.022 | 0.012 | 0.003 | 0.004 | 0.006 | 0.541 |
| 5-inside | 0.830 | 0.010 | 0.114 | 0.049 | 0.013 | 0.000 | 0.002 | 0.014 | 1.032 |
| 5-middle | 0.246 | 0.003 | 0.032 | 0.019 | 0.003 | 0.000 | 0.000 | 0.010 | 0.314 |
| 5-outside | 0.044 | 0.001 | 0.024 | 0.001 | 0.005 | 0.001 | 0.001 | 0.001 | 0.078 |
| 6-inside | 0.305 | 0.004 | 0.410 | 0.010 | 0.027 | 0.000 | 0.000 | 0.017 | 0.773 |
| 6-middle | 0.157 | 0.002 | 0.164 | 0.005 | 0.011 | 0.000 | 0.000 | 0.011 | 0.351 |
| 6-outside | 0.300 | 0.004 | 0.034 | 0.009 | 0.017 | 0.000 | 0.001 | 0.002 | 0.368 |
| 7-inside | 1.055 | 0.014 | 0.163 | 0.036 | 0.059 | 0.000 | 0.000 | 0.028 | 1.355 |
| 7-middle | 0.254 | 0.003 | 0.039 | 0.009 | 0.014 | 0.000 | 0.000 | 0.012 | 0.332 |
| 7-outside | 0.030 | 0.000 | 0.008 | 0.000 | 0.001 | 0.000 | 0.000 | 0.001 | 0.040 |
| 8-inside | 0.488 | 0.006 | 0.250 | 0.008 | 0.013 | 0.000 | 0.000 | 0.024 | 0.788 |
| 8-middle | 0.106 | 0.001 | 0.051 | 0.002 | 0.003 | 0.000 | 0.000 | 0.012 | 0.175 |
| 8-outside | 0.323 | 0.009 | 0.234 | 0.007 | 0.051 | 0.006 | 0.006 | 0.010 | 0.647 |
| 9-inside | 1.820 | 0.041 | 1.763 | 0.048 | 0.208 | 0.004 | 0.004 | 0.056 | 3.944 |
| 9-middle | 0.250 | 0.004 | 0.170 | 0.006 | 0.023 | 0.000 | 0.000 | 0.005 | 0.458 |
| 9-outside | 0.117 | 0.002 | 0.016 | 0.001 | 0.016 | 0.000 | 0.000 | 0.001 | 0.154 |
| 10-inside | 0.811 | 0.010 | 0.182 | 0.016 | 0.115 | 0.000 | 0.000 | 0.011 | 1.145 |
| 10-middle | 0.151 | 0.002 | 0.039 | 0.003 | 0.019 | 0.000 | 0.000 | 0.012 | 0.226 |
| 10-outside | 0.236 | 0.004 | 0.103 | 0.005 | 0.009 | 0.001 | 0.001 | 0.004 | 0.365 |
| 11-inside | 0.870 | 0.012 | 0.439 | 0.024 | 0.027 | 0.000 | 0.000 | 0.028 | 1.400 |
| 11-middle | 0.112 | 0.001 | 0.049 | 0.003 | 0.003 | 0.000 | 0.000 | 0.005 | 0.173 |
| 11-outside | 0.046 | 0.000 | 0.018 | 0.001 | 0.001 | 0.000 | 0.000 | 0.001 | 0.068 |
| 12-inside | 1.238 | 0.017 | 0.515 | 0.033 | 0.030 | 0.000 | 0.000 | 0.052 | 1.885 |
| 12-middle | 0.207 | 0.003 | 0.071 | 0.006 | 0.005 | 0.000 | 0.000 | 0.020 | 0.312 |
| 12-outside | 0.263 | 0.006 | 0.024 | 0.013 | 0.004 | 0.000 | 0.000 | 0.014 | 0.324 |

Monoterpenes from SYP (loblolly) increment cores: May, 1997

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 1.437 | 0.031 | 0.622 | 0.122 | 0.067 | 0.013 | 0.017 | 0.082 | 2.391 |
| 1-middle | 0.110 | 0.001 | 0.072 | 0.009 | 0.003 | 0.000 | 0.000 | 0.015 | 0.211 |
| 1-outside | 0.087 | 0.001 | 0.067 | 0.009 | 0.002 | 0.000 | 0.000 | 0.023 | 0.190 |
| 2-inside | 2.270 | 0.064 | 0.255 | 0.143 | 0.039 | 0.000 | 0.001 | 0.145 | 2.917 |
| 2-middle | 1.263 | 0.065 | 0.334 | 0.195 | 0.053 | 0.000 | 0.005 | 0.233 | 2.148 |
| 2-outside | 0.083 | 0.001 | 0.003 | 0.002 | 0.000 | 0.000 | 0.000 | 0.003 | 0.093 |
| 3-inside | 3.348 | 0.088 | 1.019 | 0.163 | 0.115 | 0.018 | 0.022 | 0.108 | 4.882 |
| 3-middle | 0.072 | 0.001 | 0.016 | 0.002 | 0.001 | 0.000 | 0.000 | 0.007 | 0.098 |
| 3-outside | 0.067 | 0.001 | 0.015 | 0.002 | 0.001 | 0.000 | 0.000 | 0.014 | 0.100 |
| 4-inside | 0.939 | 0.012 | 0.276 | 0.042 | 0.044 | 0.000 | 0.000 | 0.025 | 1.338 |
| 4-middle | 0.139 | 0.002 | 0.045 | 0.008 | 0.006 | 0.000 | 0.000 | 0.008 | 0.209 |
| 4-outside | 0.100 | 0.001 | 0.031 | 0.006 | 0.005 | 0.000 | 0.000 | 0.016 | 0.159 |
| 5-inside | 0.679 | 0.010 | 0.078 | 0.031 | 0.014 | 0.003 | 0.004 | 0.009 | 0.828 |
| 5-middle | 0.168 | 0.002 | 0.023 | 0.010 | 0.002 | 0.000 | 0.000 | 0.003 | 0.207 |
| 5-outside | 0.124 | 0.001 | 0.011 | 0.009 | 0.001 | 0.000 | 0.000 | 0.006 | 0.153 |
| 6-inside | 0.242 | 0.007 | 0.098 | 0.001 | 0.024 | 0.005 | 0.007 | 0.008 | 0.393 |
| 6-middle | 0.095 | 0.001 | 0.097 | 0.003 | 0.007 | 0.000 | 0.000 | 0.004 | 0.208 |
| 6-outside | 0.119 | 0.002 | 0.109 | 0.004 | 0.007 | 0.000 | 0.000 | 0.006 | 0.246 |
| 7-inside | 1.369 | 0.020 | 0.131 | 0.043 | 0.082 | 0.004 | 0.006 | 0.009 | 1.665 |
| 7-middle | 0.624 | 0.009 | 0.078 | 0.020 | 0.036 | 0.001 | 0.002 | 0.008 | 0.779 |
| 7-outside | 0.172 | 0.002 | 0.027 | 0.006 | 0.009 | 0.000 | 0.000 | 0.008 | 0.224 |
| 8-inside | 1.612 | 0.024 | 0.787 | 0.029 | 0.043 | 0.000 | 0.000 | 0.074 | 2.568 |
| 8-middle | 0.086 | 0.001 | 0.043 | 0.001 | 0.002 | 0.000 | 0.000 | 0.006 | 0.139 |
| 8-outside | 0.067 | 0.001 | 0.030 | 0.001 | 0.001 | 0.000 | 0.000 | 0.009 | 0.109 |
| 9-inside | 1.335 | 0.032 | 0.697 | 0.022 | 0.182 | 0.021 | 0.021 | 0.033 | 2.343 |
| 9-middle | 0.442 | 0.013 | 0.188 | 0.007 | 0.062 | 0.010 | 0.011 | 0.012 | 0.746 |
| 9-outside | 0.271 | 0.004 | 0.191 | 0.007 | 0.029 | 0.000 | 0.000 | 0.004 | 0.506 |
| 10-inside | 0.242 | 0.003 | 0.055 | 0.003 | 0.035 | 0.000 | 0.000 | 0.005 | 0.343 |
| 10-middle | 0.100 | 0.001 | 0.025 | 0.002 | 0.013 | 0.000 | 0.000 | 0.004 | 0.146 |
| 10-outside | 0.114 | 0.001 | 0.031 | 0.002 | 0.013 | 0.000 | 0.000 | 0.013 | 0.175 |
| 11-inside | 0.775 | 0.012 | 0.363 | 0.018 | 0.027 | 0.002 | 0.002 | 0.015 | 1.213 |
| 11-middle | 0.532 | 0.011 | 0.350 | 0.019 | 0.029 | 0.004 | 0.004 | 0.012 | 0.961 |
| 11-outside | 0.083 | 0.001 | 0.034 | 0.002 | 0.002 | 0.000 | 0.000 | 0.005 | 0.126 |
| 12-inside | 1.143 | 0.016 | 0.448 | 0.028 | 0.028 | 0.000 | 0.000 | 0.028 | 1.692 |
| 12-middle | 0.178 | 0.002 | 0.074 | 0.004 | 0.004 | 0.000 | 0.000 | 0.010 | 0.273 |
| 12-outside | 0.144 | 0.002 | 0.046 | 0.004 | 0.003 | 0.000 | 0.000 | 0.015 | 0.214 |

**Monoterpenes from SYP (loblolly) increment cores: June, 1997**

***Concentration (g/g OD wood, %)***

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 0.368 | 0.005 | 0.240 | 0.017 | 0.013 | 0.001 | 0.002 | 0.028 | 0.674 |
| 1-middle | 0.080 | 0.001 | 0.061 | 0.008 | 0.002 | 0.000 | 0.000 | 0.013 | 0.165 |
| 1-outside | 0.075 | 0.001 | 0.077 | 0.005 | 0.002 | 0.000 | 0.000 | 0.019 | 0.179 |
| 2-inside | 1.431 | 0.018 | 0.064 | 0.026 | 0.014 | 0.000 | 0.001 | 0.015 | 1.568 |
| 2-middle | 0.658 | 0.012 | 0.039 | 0.030 | 0.007 | 0.000 | 0.000 | 0.000 | 0.746 |
| 2-outside | 0.114 | 0.001 | 0.005 | 0.003 | 0.001 | 0.000 | 0.000 | 0.000 | 0.124 |
| 3-inside | 4.448 | 0.130 | 2.142 | 0.268 | 0.159 | 0.015 | 0.018 | 0.121 | 7.302 |
| 3-middle | 0.121 | 0.001 | 0.039 | 0.002 | 0.002 | 0.000 | 0.000 | 0.014 | 0.179 |
| 3-outside | 0.086 | 0.001 | 0.027 | 0.003 | 0.001 | 0.000 | 0.000 | 0.021 | 0.139 |
| 4-inside | 0.201 | 0.000 | 0.059 | 0.005 | 0.008 | 0.000 | 0.000 | 0.008 | 0.280 |
| 4-middle | 0.095 | 0.001 | 0.034 | 0.006 | 0.005 | 0.000 | 0.000 | 0.015 | 0.156 |
| 4-outside | 0.080 | 0.000 | 0.033 | 0.003 | 0.003 | 0.000 | 0.000 | 0.021 | 0.141 |
| 5-inside | 1.114 | 0.027 | 0.076 | 0.047 | 0.047 | 0.013 | 0.016 | 0.118 | 1.459 |
| 5-middle | 0.164 | 0.002 | 0.018 | 0.008 | 0.001 | 0.000 | 0.000 | 0.004 | 0.197 |
| 5-outside | 0.160 | 0.002 | 0.011 | 0.006 | 0.001 | 0.000 | 0.000 | 0.005 | 0.185 |
| 6-inside | 0.346 | 0.016 | 0.093 | 0.004 | 0.065 | 0.014 | 0.015 | 0.124 | 0.677 |
| 6-middle | 0.085 | 0.001 | 0.105 | 0.003 | 0.006 | 0.000 | 0.000 | 0.001 | 0.202 |
| 6-outside | 0.920 | 0.016 | 0.079 | 0.031 | 0.063 | 0.005 | 0.006 | 0.046 | 1.168 |
| 7-inside | 1.938 | 0.034 | 0.167 | 0.066 | 0.133 | 0.011 | 0.014 | 0.097 | 2.459 |
| 7-middle | 0.184 | 0.002 | 0.035 | 0.004 | 0.009 | 0.000 | 0.000 | 0.005 | 0.239 |
| 7-outside | 0.147 | 0.002 | 0.032 | 0.003 | 0.007 | 0.000 | 0.000 | 0.006 | 0.197 |
| 8-inside | 0.315 | 0.004 | 0.150 | 0.003 | 0.010 | 0.001 | 0.001 | 0.023 | 0.506 |
| 8-middle | 0.272 | 0.004 | 0.160 | 0.003 | 0.008 | 0.000 | 0.000 | 0.004 | 0.452 |
| 8-outside | 0.072 | 0.001 | 0.033 | 0.001 | 0.001 | 0.000 | 0.000 | 0.011 | 0.120 |
| 9-inside | 0.287 | 0.010 | 0.121 | 0.003 | 0.046 | 0.009 | 0.009 | 0.082 | 0.566 |
| 9-middle | 0.184 | 0.005 | 0.095 | 0.003 | 0.001 | 0.003 | 0.003 | 0.030 | 0.324 |
| 9-outside | 0.202 | 0.003 | 0.161 | 0.003 | 0.016 | 0.000 | 0.000 | 0.004 | 0.389 |
| 10-inside | 0.926 | 0.017 | 0.267 | 0.012 | 0.154 | 0.000 | 0.000 | 0.025 | 1.400 |
| 10-middle | 0.096 | 0.001 | 0.022 | 0.002 | 0.012 | 0.000 | 0.000 | 0.003 | 0.136 |
| 10-outside | 0.109 | 0.001 | 0.027 | 0.002 | 0.011 | 0.000 | 0.000 | 0.009 | 0.159 |
| 11-inside | 1.818 | 0.052 | 1.080 | 0.087 | 0.106 | 0.005 | 0.006 | 0.046 | 3.199 |
| 11-middle | 0.375 | 0.005 | 0.185 | 0.010 | 0.011 | 0.000 | 0.000 | 0.008 | 0.593 |
| 11-outside | 0.105 | 0.001 | 0.035 | 0.003 | 0.002 | 0.000 | 0.000 | 0.007 | 0.153 |
| 12-inside | 1.820 | 0.027 | 0.828 | 0.027 | 0.046 | 0.001 | 0.001 | 0.024 | 2.775 |
| 12-middle | 1.291 | 0.028 | 0.779 | 0.053 | 0.045 | 0.000 | 0.000 | 0.063 | 2.259 |
| 12-outside | 0.179 | 0.002 | 0.062 | 0.005 | 0.005 | 0.000 | 0.000 | 0.016 | 0.268 |

Monoterpenes from SYP (loblolly) increment cores: July, 1997

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 1.338 | 0.032 | 1.187 | 0.175 | 0.062 | 0.004 | 0.005 | 0.114 | 2.918 |
| 1-middle | 0.163 | 0.002 | 0.117 | 0.017 | 0.004 | 0.000 | 0.000 | 0.026 | 0.328 |
| 1-outside | 0.094 | 0.001 | 0.078 | 0.011 | 0.003 | 0.000 | 0.000 | 0.021 | 0.208 |
| 2-inside | 2.184 | 0.103 | 0.415 | 0.230 | 0.064 | 0.000 | 0.001 | 0.247 | 3.244 |
| 2-middle | 2.810 | 0.081 | 0.231 | 0.175 | 0.051 | 0.000 | 0.001 | 0.230 | 3.579 |
| 2-outside | 0.099 | 0.000 | 0.006 | 0.003 | 0.000 | 0.000 | 0.000 | 0.005 | 0.113 |
| 3-inside | 2.316 | 0.077 | 1.228 | 0.161 | 0.082 | 0.004 | 0.004 | 0.094 | 3.965 |
| 3-middle | 0.273 | 0.004 | 0.040 | 0.008 | 0.003 | 0.000 | 0.000 | 0.017 | 0.345 |
| 3-outside | 0.153 | 0.002 | 0.027 | 0.005 | 0.002 | 0.000 | 0.000 | 0.024 | 0.213 |
| 4-inside | 1.537 | 0.090 | 0.242 | 0.077 | 0.208 | 0.030 | 0.042 | 0.174 | 2.399 |
| 4-middle | 0.154 | 0.002 | 0.054 | 0.009 | 0.008 | 0.000 | 0.000 | 0.013 | 0.239 |
| 4-outside | 0.126 | 0.002 | 0.046 | 0.008 | 0.006 | 0.000 | 0.000 | 0.022 | 0.210 |
| 5-inside | 0.680 | 0.008 | 0.083 | 0.031 | 0.013 | 0.000 | 0.000 | 0.010 | 0.825 |
| 5-middle | 0.453 | 0.005 | 0.048 | 0.024 | 0.005 | 0.000 | 0.000 | 0.009 | 0.544 |
| 5-outside | 0.195 | 0.002 | 0.020 | 0.009 | 0.004 | 0.000 | 0.000 | 0.010 | 0.239 |
| 6-inside | 0.828 | 0.048 | 0.144 | 0.018 | 0.216 | 0.040 | 0.039 | 0.031 | 1.365 |
| 6-middle | 0.201 | 0.006 | 0.156 | 0.004 | 0.024 | 0.005 | 0.005 | 0.029 | 0.430 |
| 6-outside | 0.178 | 0.002 | 0.162 | 0.005 | 0.009 | 0.000 | 0.000 | 0.015 | 0.373 |
| 7-inside | 2.365 | 0.080 | 0.377 | 0.152 | 0.278 | 0.018 | 0.024 | 0.019 | 3.312 |
| 7-middle | 0.282 | 0.004 | 0.043 | 0.009 | 0.015 | 0.000 | 0.000 | 0.006 | 0.359 |
| 7-outside | 0.311 | 0.004 | 0.048 | 0.011 | 0.016 | 0.000 | 0.000 | 0.011 | 0.401 |
| 8-inside | 1.914 | 0.099 | 0.667 | 0.031 | 0.148 | 0.036 | 0.043 | 0.065 | 3.003 |
| 8-middle | 1.079 | 0.020 | 0.311 | 0.011 | 0.001 | 0.004 | 0.004 | 0.026 | 1.457 |
| 8-outside | 0.128 | 0.001 | 0.058 | 0.001 | 0.004 | 0.000 | 0.000 | 0.008 | 0.200 |
| 9-inside | 1.211 | 0.032 | 0.608 | 0.020 | 0.156 | 0.020 | 0.021 | 0.114 | 2.183 |
| 9-middle | 1.262 | 0.037 | 1.120 | 0.038 | 0.120 | 0.003 | 0.002 | 0.034 | 2.615 |
| 9-outside | 0.260 | 0.003 | 0.172 | 0.006 | 0.021 | 0.000 | 0.000 | 0.002 | 0.464 |
| 10-inside | 0.623 | 0.008 | 0.130 | 0.009 | 0.084 | 0.001 | 0.001 | 0.012 | 0.867 |
| 10-middle | 1.285 | 0.024 | 0.435 | 0.036 | 0.228 | 0.000 | 0.000 | 0.051 | 2.059 |
| 10-outside | 0.105 | 0.001 | 0.032 | 0.001 | 0.012 | 0.000 | 0.000 | 0.008 | 0.160 |
| 11-inside | 1.639 | 0.030 | 0.657 | 0.034 | 0.071 | 0.012 | 0.012 | 0.022 | 2.476 |
| 11-middle | 0.537 | 0.007 | 0.246 | 0.014 | 0.015 | 0.000 | 0.000 | 0.020 | 0.840 |
| 11-outside | 0.122 | 0.001 | 0.042 | 0.003 | 0.002 | 0.000 | 0.000 | 0.008 | 0.179 |
| 12-inside | 0.446 | 0.005 | 0.163 | 0.009 | 0.011 | 0.000 | 0.000 | 0.011 | 0.645 |
| 12-middle | 0.206 | 0.003 | 0.085 | 0.006 | 0.005 | 0.000 | 0.000 | 0.007 | 0.311 |
| 12-outside | 0.202 | 0.002 | 0.063 | 0.005 | 0.004 | 0.000 | 0.000 | 0.017 | 0.293 |

**Monoterpenes from SYP (loblolly) increment cores: August, 1997**

***Concentration (g/g OD wood, %)***

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 2.215 | 0.034 | 1.253 | 0.244 | 0.064 | 0.008 | 0.009 | 0.170 | 3.997 |
| 1-middle | 0.104 | 0.001 | 0.081 | 0.009 | 0.001 | 0.000 | 0.000 | 0.013 | 0.208 |
| 1-outside | 0.116 | 0.001 | 0.091 | 0.012 | 0.001 | 0.000 | 0.000 | 0.018 | 0.240 |
| 2-inside | 3.228 | 0.118 | 0.427 | 0.283 | 0.070 | 0.000 | 0.004 | 0.244 | 4.375 |
| 2-middle | 2.394 | 0.084 | 0.219 | 0.204 | 0.050 | 0.000 | 0.002 | 0.207 | 3.161 |
| 2-outside | 0.161 | 0.000 | 0.036 | 0.005 | 0.000 | 0.000 | 0.000 | 0.007 | 0.208 |
| 3-inside | 2.250 | 0.081 | 1.251 | 0.167 | 0.096 | 0.010 | 0.011 | 0.111 | 3.977 |
| 3-middle | 0.168 | 0.001 | 0.030 | 0.004 | 0.001 | 0.000 | 0.000 | 0.014 | 0.217 |
| 3-outside | 0.147 | 0.001 | 0.026 | 0.003 | 0.000 | 0.000 | 0.000 | 0.027 | 0.204 |
| 4-inside | 0.267 | 0.002 | 0.055 | 0.008 | 0.013 | 0.000 | 0.001 | 0.021 | 0.367 |
| 4-middle | 0.666 | 0.008 | 0.217 | 0.038 | 0.030 | 0.000 | 0.000 | 0.037 | 0.996 |
| 4-outside | 0.123 | 0.000 | 0.035 | 0.004 | 0.003 | 0.000 | 0.000 | 0.014 | 0.179 |
| 5-inside | 1.126 | 0.020 | 0.095 | 0.048 | 0.030 | 0.008 | 0.011 | 0.073 | 1.410 |
| 5-middle | 0.198 | 0.001 | 0.038 | 0.010 | 0.001 | 0.000 | 0.000 | 0.002 | 0.249 |
| 5-outside | 0.159 | 0.001 | 0.020 | 0.010 | 0.001 | 0.000 | 0.000 | 0.009 | 0.200 |
| 6-inside | 1.607 | 0.045 | 0.912 | 0.037 | 0.002 | 0.028 | 0.029 | 0.051 | 2.712 |
| 6-middle | 0.168 | 0.002 | 0.136 | 0.002 | 0.016 | 0.001 | 0.001 | 0.006 | 0.331 |
| 6-outside | 0.147 | 0.001 | 0.099 | 0.003 | 0.006 | 0.000 | 0.000 | 0.013 | 0.268 |
| 7-inside | 1.899 | 0.027 | 0.176 | 0.050 | 0.095 | 0.003 | 0.003 | 0.038 | 2.292 |
| 7-middle | 0.224 | 0.002 | 0.030 | 0.005 | 0.009 | 0.000 | 0.000 | 0.004 | 0.272 |
| 7-outside | 0.227 | 0.001 | 0.032 | 0.006 | 0.010 | 0.000 | 0.000 | 0.008 | 0.283 |
| 8-inside | 0.354 | 0.005 | 0.117 | 0.001 | 0.013 | 0.001 | 0.002 | 0.010 | 0.503 |
| 8-middle | 0.117 | 0.000 | 0.054 | 0.001 | 0.003 | 0.000 | 0.000 | 0.007 | 0.181 |
| 8-outside | 0.089 | 0.000 | 0.040 | 0.000 | 0.001 | 0.000 | 0.000 | 0.013 | 0.143 |
| 9-inside | 1.545 | 0.040 | 0.936 | 0.028 | 0.225 | 0.023 | 0.023 | 0.039 | 2.859 |
| 9-middle | 0.939 | 0.019 | 0.624 | 0.019 | 0.111 | 0.007 | 0.007 | 0.021 | 1.747 |
| 9-outside | 0.294 | 0.003 | 0.213 | 0.005 | 0.025 | 0.000 | 0.000 | 0.003 | 0.543 |
| 10-inside | 1.440 | 0.030 | 0.159 | 0.020 | 0.212 | 0.008 | 0.009 | 0.013 | 1.891 |
| 10-middle | 1.664 | 0.036 | 0.806 | 0.069 | 0.443 | 0.000 | 0.005 | 0.100 | 3.123 |
| 10-outside | 0.110 | 0.001 | 0.026 | 0.001 | 0.012 | 0.000 | 0.000 | 0.012 | 0.160 |
| 11-inside | 1.171 | 0.023 | 0.479 | 0.026 | 0.053 | 0.009 | 0.010 | 0.021 | 1.791 |
| 11-middle | 0.108 | 0.000 | 0.052 | 0.001 | 0.002 | 0.000 | 0.000 | 0.005 | 0.168 |
| 11-outside | 0.156 | 0.001 | 0.070 | 0.003 | 0.005 | 0.000 | 0.000 | 0.009 | 0.243 |
| 12-inside | 1.801 | 0.024 | 0.636 | 0.040 | 0.046 | 0.000 | 0.000 | 0.038 | 2.586 |
| 12-middle | 0.198 | 0.001 | 0.080 | 0.003 | 0.003 | 0.000 | 0.000 | 0.005 | 0.291 |
| 12-outside | 0.230 | 0.002 | 0.078 | 0.004 | 0.004 | 0.000 | 0.000 | 0.016 | 0.334 |

Monoterpenes from SYP (loblolly) increment cores: October, 1997

*Concentration (g/g OD wood, %)* *First samples from 2nd set of trees*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 1.966 | 0.085 | 1.315 | 0.100 | 0.482 | 0.016 | 0.018 | 0.000 | 3.982 |
| 1-middle | 0.152 | 0.002 | 0.036 | 0.003 | 0.004 | 0.000 | 0.000 | 0.002 | 0.198 |
| 1-outside | 0.181 | 0.003 | 0.052 | 0.003 | 0.005 | 0.000 | 0.000 | 0.007 | 0.251 |
| 2-inside | 1.807 | 0.086 | 1.374 | 0.106 | 0.662 | 0.055 | 0.050 | 0.103 | 4.242 |
| 2-middle | 0.574 | 0.022 | 0.307 | 0.021 | 0.065 | 0.004 | 0.004 | 0.036 | 1.035 |
| 2-outside | 0.376 | 0.006 | 0.086 | 0.007 | 0.012 | 0.000 | 0.000 | 0.015 | 0.501 |
| 3-inside | 1.069 | 0.038 | 0.239 | 0.021 | 0.202 | 0.026 | 0.027 | 0.158 | 1.779 |
| 3-middle | 0.616 | 0.034 | 0.467 | 0.040 | 0.203 | 0.016 | 0.015 | 0.029 | 1.420 |
| 3-outside | 0.360 | 0.007 | 0.126 | 0.009 | 0.054 | 0.000 | 0.000 | 0.021 | 0.577 |
| 4-inside | 1.329 | 0.060 | 0.552 | 0.051 | 0.584 | 0.058 | 0.056 | 0.088 | 2.778 |
| 4-middle | 0.420 | 0.009 | 0.204 | 0.010 | 0.033 | 0.000 | 0.000 | 0.017 | 0.694 |
| 4-outside | 0.542 | 0.016 | 0.390 | 0.018 | 0.102 | 0.003 | 0.003 | 0.034 | 1.108 |
| 5-inside | 1.088 | 0.058 | 1.062 | 0.058 | 0.004 | 0.077 | 0.071 | 0.057 | 2.475 |
| 5-middle | 0.381 | 0.007 | 3.077 | 0.010 | 0.052 | 0.002 | 0.002 | 0.014 | 3.547 |
| 5-outside | 0.317 | 0.005 | 0.182 | 0.007 | 0.022 | 0.000 | 0.000 | 0.019 | 0.553 |
| 6-inside | 0.571 | 0.014 | 0.097 | 0.007 | 0.104 | 0.006 | 0.007 | 0.010 | 0.816 |
| 6-middle | 0.361 | 0.007 | 0.124 | 0.011 | 0.102 | 0.000 | 0.000 | 0.011 | 0.615 |
| 6-outside | 0.340 | 0.005 | 0.067 | 0.007 | 0.051 | 0.000 | 0.000 | 0.016 | 0.487 |
| 7-inside | 1.188 | 0.049 | 0.064 | 0.042 | 0.550 | 0.029 | 0.034 | 0.060 | 2.016 |
| 7-middle | 0.335 | 0.009 | 0.033 | 0.013 | 0.216 | 0.002 | 0.002 | 0.024 | 0.635 |
| 7-outside | 0.171 | 0.004 | 0.019 | 0.006 | 0.100 | 0.000 | 0.000 | 0.017 | 0.317 |
| 8-inside | 1.060 | 0.035 | 0.181 | 0.022 | 0.081 | 0.011 | 0.013 | 0.056 | 1.460 |
| 8-middle | 0.364 | 0.008 | 0.045 | 0.001 | 0.022 | 0.001 | 0.002 | 0.007 | 0.449 |
| 8-outside | 0.316 | 0.004 | 0.024 | 0.005 | 0.015 | 0.000 | 0.000 | 0.015 | 0.380 |
| 9-inside | 0.411 | 0.006 | 0.198 | 0.006 | 0.033 | 0.000 | 0.000 | 0.016 | 0.671 |
| 9-middle | 0.211 | 0.003 | 0.105 | 0.004 | 0.020 | 0.000 | 0.000 | 0.008 | 0.351 |
| 9-outside | 0.241 | 0.004 | 0.096 | 0.005 | 0.018 | 0.000 | 0.000 | 0.033 | 0.396 |
| 10-inside | 1.389 | 0.035 | 0.351 | 0.023 | 0.118 | 0.018 | 0.017 | 0.061 | 2.012 |
| 10-middle | 0.341 | 0.008 | 0.090 | 0.006 | 0.024 | 0.002 | 0.002 | 0.029 | 0.502 |
| 10-outside | 0.229 | 0.003 | 0.040 | 0.003 | 0.009 | 0.000 | 0.000 | 0.020 | 0.306 |
| 11-inside | 1.723 | 0.066 | 1.511 | 0.064 | 0.260 | 0.039 | 0.034 | 0.069 | 3.765 |
| 11-middle | 0.301 | 0.013 | 0.149 | 0.007 | 0.044 | 0.011 | 0.011 | 0.018 | 0.552 |
| 11-outside | 0.248 | 0.004 | 0.145 | 0.007 | 0.024 | 0.000 | 0.000 | 0.031 | 0.460 |
| 12-inside | 2.108 | 0.127 | 0.958 | 0.111 | 0.297 | 0.057 | 0.061 | 0.074 | 3.793 |
| 12-middle | 0.779 | 0.055 | 0.525 | 0.030 | 0.101 | 0.024 | 0.025 | 0.036 | 1.575 |
| 12-outside | 0.413 | 0.022 | 0.395 | 0.029 | 0.080 | 0.014 | 0.013 | 0.025 | 0.990 |

**Monoterpenes from SYP (loblolly) increment cores: November, 1997**

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 1.448 | 0.080 | 0.999 | 0.073 | 0.404 | 0.025 | 0.027 | 0.042 | 3.096 |
| 1-middle | 0.385 | 0.020 | 0.224 | 0.019 | 0.039 | 0.003 | 0.003 | 0.010 | 0.703 |
| 1-outside | 0.192 | 0.003 | 0.045 | 0.003 | 0.006 | 0.000 | 0.000 | 0.006 | 0.255 |
| 2-inside | 2.662 | 0.119 | 2.015 | 0.115 | 0.730 | 0.062 | 0.058 | 0.144 | 5.905 |
| 2-middle | 0.633 | 0.033 | 0.447 | 0.035 | 0.117 | 0.005 | 0.006 | 0.064 | 1.340 |
| 2-outside | 0.193 | 0.003 | 0.045 | 0.003 | 0.006 | 0.000 | 0.000 | 0.009 | 0.258 |
| 3-inside | 1.051 | 0.041 | 0.296 | 0.025 | 0.246 | 0.029 | 0.029 | 0.032 | 1.748 |
| 3-middle | 0.603 | 0.036 | 0.479 | 0.047 | 0.266 | 0.015 | 0.014 | 0.051 | 1.510 |
| 3-outside | 0.295 | 0.006 | 0.103 | 0.007 | 0.040 | 0.000 | 0.000 | 0.020 | 0.471 |
| 4-inside | 1.286 | 0.106 | 0.875 | 0.082 | 0.822 | 0.064 | 0.064 | 0.130 | 3.431 |
| 4-middle | 0.578 | 0.021 | 0.402 | 0.020 | 0.111 | 0.004 | 0.005 | 0.039 | 1.181 |
| 4-outside | 0.314 | 0.005 | 0.127 | 0.006 | 0.016 | 0.000 | 0.000 | 0.014 | 0.482 |
| 5-inside | 0.974 | 0.038 | 0.744 | 0.031 | 0.001 | 0.045 | 0.041 | 0.338 | 2.213 |
| 5-middle | 0.283 | 0.008 | 0.239 | 0.009 | 0.054 | 0.007 | 0.006 | 0.012 | 0.619 |
| 5-outside | 0.224 | 0.004 | 0.152 | 0.006 | 0.018 | 0.000 | 0.000 | 0.015 | 0.419 |
| 6-inside | 0.626 | 0.014 | 0.139 | 0.011 | 0.001 | 0.004 | 0.005 | 0.010 | 0.810 |
| 6-middle | 0.198 | 0.003 | 0.061 | 0.005 | 0.051 | 0.000 | 0.000 | 0.008 | 0.327 |
| 6-outside | 0.193 | 0.003 | 0.033 | 0.005 | 0.037 | 0.000 | 0.000 | 0.020 | 0.292 |
| 7-inside | 0.983 | 0.257 | 0.068 | 0.035 | 0.394 | 0.024 | 0.026 | 0.042 | 1.830 |
| 7-middle | 0.735 | 0.061 | 0.222 | 0.072 | 0.617 | 0.009 | 0.010 | 0.138 | 1.865 |
| 7-outside | 0.137 | 0.003 | 0.013 | 0.005 | 0.000 | 0.000 | 0.000 | 0.013 | 0.171 |
| 8-inside | 1.074 | 0.054 | 0.240 | 0.030 | 0.124 | 0.032 | 0.033 | 0.042 | 1.628 |
| 8-middle | 0.136 | 0.004 | 0.027 | 0.004 | 0.011 | 0.002 | 0.003 | 0.008 | 0.196 |
| 8-outside | 0.251 | 0.004 | 0.022 | 0.004 | 0.011 | 0.000 | 0.000 | 0.000 | 0.291 |
| 9-inside | 1.384 | 0.066 | 0.294 | 0.036 | 0.150 | 0.038 | 0.038 | 0.048 | 2.054 |
| 9-middle | 0.193 | 0.004 | 0.098 | 0.004 | 0.016 | 0.001 | 0.002 | 0.016 | 0.334 |
| 9-outside | 0.208 | 0.003 | 0.097 | 0.005 | 0.018 | 0.000 | 0.000 | 0.012 | 0.343 |
| 10-inside | 1.355 | 0.104 | 0.870 | 0.066 | 0.448 | 0.081 | 0.080 | 0.210 | 3.214 |
| 10-middle | 0.840 | 0.067 | 0.554 | 0.054 | 0.261 | 0.029 | 0.033 | 0.217 | 2.054 |
| 10-outside | 0.175 | 0.002 | 0.041 | 0.003 | 0.009 | 0.000 | 0.000 | 0.008 | 0.237 |
| 11-inside | 0.738 | 0.060 | 0.486 | 0.062 | 0.360 | 0.074 | 0.082 | 0.053 | 1.914 |
| 11-middle | 0.460 | 0.035 | 0.417 | 0.037 | 0.160 | 0.018 | 0.018 | 0.088 | 1.234 |
| 11-outside | 0.291 | 0.007 | 0.210 | 0.009 | 0.032 | 0.002 | 0.002 | 0.026 | 0.578 |
| 12-inside | 1.863 | 0.145 | 0.833 | 0.101 | 0.273 | 0.047 | 0.051 | 0.092 | 3.404 |
| 12-middle | 0.466 | 0.031 | 0.393 | 0.019 | 0.079 | 0.022 | 0.022 | 0.020 | 1.052 |
| 12-outside | 0.309 | 0.010 | 0.197 | 0.009 | 0.024 | 0.003 | 0.003 | 0.016 | 0.571 |

Monoterpenes from SYP (loblolly) increment cores: December, 1997

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 1.497 | 0.066 | 1.020 | 0.079 | 0.332 | 0.006 | 0.026 | 0.002 | 3.028 |
| 1-middle | 0.543 | 0.020 | 0.191 | 0.017 | 0.039 | 0.005 | 0.005 | 0.011 | 0.830 |
| 1-outside | 0.218 | 0.003 | 0.052 | 0.004 | 0.006 | 0.000 | 0.000 | 0.007 | 0.290 |
| 2-inside | 1.604 | 0.066 | 1.222 | 0.080 | 0.001 | 0.004 | 0.049 | 0.072 | 3.097 |
| 2-middle | 0.676 | 0.029 | 0.446 | 0.031 | 0.099 | 0.004 | 0.004 | 0.058 | 1.348 |
| 2-outside | 0.278 | 0.004 | 0.073 | 0.005 | 0.009 | 0.000 | 0.000 | 0.012 | 0.380 |
| 3-inside | 0.916 | 0.041 | 0.313 | 0.030 | 0.283 | 0.002 | 0.044 | 0.039 | 1.667 |
| 3-middle | 0.561 | 0.029 | 0.451 | 0.031 | 0.209 | 0.001 | 0.017 | 0.032 | 1.332 |
| 3-outside | 0.287 | 0.005 | 0.080 | 0.006 | 0.030 | 0.000 | 0.000 | 0.056 | 0.464 |
| 4-inside | 1.114 | 0.048 | 0.731 | 0.047 | 0.472 | 0.035 | 0.035 | 0.062 | 2.545 |
| 4-middle | 0.396 | 0.012 | 0.258 | 0.014 | 0.078 | 0.001 | 0.003 | 0.031 | 0.791 |
| 4-outside | 0.245 | 0.004 | 0.090 | 0.005 | 0.012 | 0.000 | 0.000 | 0.012 | 0.368 |
| 5-inside | 0.775 | 0.024 | 0.373 | 0.023 | 0.221 | 0.041 | 0.037 | 0.025 | 1.519 |
| 5-middle | 0.254 | 0.005 | 0.203 | 0.007 | 0.030 | 0.001 | 0.001 | 0.007 | 0.507 |
| 5-outside | 0.244 | 0.004 | 0.136 | 0.006 | 0.014 | 0.000 | 0.000 | 0.013 | 0.417 |
| 6-inside | 1.015 | 0.019 | 0.259 | 0.021 | 0.219 | 0.003 | 0.004 | 0.015 | 1.553 |
| 6-middle | 0.181 | 0.004 | 0.075 | 0.006 | 0.061 | 0.000 | 0.000 | 0.008 | 0.335 |
| 6-outside | 0.224 | 0.004 | 0.054 | 0.005 | 0.041 | 0.000 | 0.000 | 0.012 | 0.340 |
| 7-inside | 1.104 | 0.040 | 0.079 | 0.046 | 0.645 | 0.021 | 0.022 | 0.077 | 2.034 |
| 7-middle | 0.490 | 0.025 | 0.106 | 0.038 | 0.406 | 0.009 | 0.005 | 0.004 | 1.083 |
| 7-outside | 0.175 | 0.003 | 0.016 | 0.005 | 0.066 | 0.000 | 0.000 | 0.014 | 0.280 |
| 8-inside | 1.143 | 0.053 | 0.436 | 0.040 | 0.194 | 0.031 | 0.046 | 0.031 | 1.974 |
| 8-middle | 0.733 | 0.048 | 0.544 | 0.047 | 0.188 | 0.022 | 0.031 | 0.038 | 1.649 |
| 8-outside | 0.245 | 0.004 | 0.023 | 0.004 | 0.011 | 0.000 | 0.000 | 0.012 | 0.298 |
| 9-inside | 1.423 | 0.033 | 0.947 | 0.036 | 0.116 | 0.016 | 0.017 | 0.045 | 2.635 |
| 9-middle | 0.345 | 0.007 | 0.188 | 0.007 | 0.035 | 0.005 | 0.005 | 0.015 | 0.607 |
| 9-outside | 0.214 | 0.003 | 0.105 | 0.005 | 0.019 | 0.000 | 0.000 | 0.032 | 0.378 |
| 10-inside | 1.517 | 0.057 | 0.837 | 0.055 | 0.245 | 0.031 | 0.043 | 0.133 | 2.916 |
| 10-middle | 0.227 | 0.007 | 0.062 | 0.005 | 0.025 | 0.004 | 0.004 | 0.020 | 0.355 |
| 10-outside | 0.143 | 0.003 | 0.045 | 0.003 | 0.000 | 0.000 | 0.000 | 0.013 | 0.207 |
| 11-inside | 1.367 | 0.046 | 1.182 | 0.062 | 0.312 | 0.036 | 0.035 | 0.089 | 3.129 |
| 11-middle | 0.835 | 0.049 | 0.812 | 0.064 | 0.203 | 0.001 | 0.000 | 0.060 | 2.023 |
| 11-outside | 0.162 | 0.003 | 0.095 | 0.005 | 0.021 | 0.000 | 0.000 | 0.015 | 0.301 |
| 12-inside | 1.853 | 0.102 | 0.682 | 0.091 | 0.273 | 0.003 | 0.010 | 0.067 | 3.080 |
| 12-middle | 0.802 | 0.057 | 0.432 | 0.042 | 0.133 | 0.019 | 0.022 | 0.040 | 1.546 |
| 12-outside | 0.516 | 0.020 | 0.466 | 0.026 | 0.076 | 0.009 | 0.013 | 0.048 | 1.174 |

**Monoterpenes from SYP (loblolly) increment cores: January, 1998**

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 2.110 | 0.081 | 1.448 | 0.096 | 0.438 | 0.020 | 0.021 | 0.043 | 4.257 |
| 1-middle | 0.319 | 0.005 | 0.072 | 0.006 | 0.009 | 0.000 | 0.000 | 0.008 | 0.419 |
| 1-outside | 0.432 | 0.008 | 0.141 | 0.009 | 0.023 | 0.000 | 0.000 | 0.016 | 0.628 |
| 2-inside | 1.576 | 0.066 | 1.129 | 0.078 | 0.503 | 0.004 | 0.048 | 0.071 | 3.474 |
| 2-middle | 0.624 | 0.009 | 0.129 | 0.010 | 0.018 | 0.000 | 0.000 | 0.024 | 0.814 |
| 2-outside | 0.599 | 0.009 | 0.124 | 0.009 | 0.017 | 0.000 | 0.000 | 0.023 | 0.781 |
| 3-inside | 1.361 | 0.045 | 0.858 | 0.044 | 0.409 | 0.003 | 0.031 | 0.061 | 2.812 |
| 3-middle | 0.792 | 0.033 | 0.623 | 0.036 | 0.245 | 0.002 | 0.004 | 0.002 | 1.737 |
| 3-outside | 0.507 | 0.008 | 0.148 | 0.010 | 0.055 | 0.000 | 0.000 | 0.023 | 0.750 |
| 4-inside | 1.621 | 0.069 | 0.569 | 0.058 | 0.689 | 0.073 | 0.071 | 0.092 | 3.243 |
| 4-middle | 0.416 | 0.019 | 0.286 | 0.022 | 0.127 | 0.002 | 0.010 | 0.048 | 0.930 |
| 4-outside | 0.694 | 0.012 | 0.355 | 0.015 | 0.040 | 0.000 | 0.000 | 0.033 | 1.149 |
| 5-inside | 1.057 | 0.031 | 0.474 | 0.028 | 0.271 | 0.051 | 0.047 | 0.029 | 1.987 |
| 5-middle | 0.501 | 0.012 | 0.413 | 0.015 | 0.102 | 0.000 | 0.012 | 0.018 | 1.074 |
| 5-outside | 0.421 | 0.008 | 0.273 | 0.011 | 0.030 | 0.000 | 0.000 | 0.024 | 0.767 |
| 6-inside | 0.701 | 0.014 | 0.146 | 0.011 | 0.135 | 0.005 | 0.005 | 0.012 | 1.029 |
| 6-middle | 0.430 | 0.007 | 0.133 | 0.011 | 0.104 | 0.000 | 0.000 | 0.022 | 0.708 |
| 6-outside | 0.512 | 0.008 | 0.133 | 0.012 | 0.097 | 0.000 | 0.000 | 0.058 | 0.822 |
| 7-inside | 1.153 | 0.052 | 0.053 | 0.039 | 0.492 | 0.026 | 0.030 | 0.056 | 1.901 |
| 7-middle | 0.623 | 0.020 | 0.048 | 0.023 | 0.320 | 0.005 | 0.004 | 0.002 | 1.046 |
| 7-outside | 0.203 | 0.004 | 0.018 | 0.005 | 0.063 | 0.000 | 0.000 | 0.018 | 0.311 |
| 8-inside | 1.475 | 0.055 | 0.340 | 0.035 | 0.219 | 0.046 | 0.045 | 0.064 | 2.279 |
| 8-middle | 0.647 | 0.030 | 0.106 | 0.017 | 0.090 | 0.001 | 0.005 | 0.000 | 0.896 |
| 8-outside | 0.342 | 0.005 | 0.032 | 0.006 | 0.021 | 0.000 | 0.000 | 0.021 | 0.426 |
| 9-inside | 1.750 | 0.079 | 1.258 | 0.081 | 0.632 | 0.005 | 0.060 | 0.001 | 3.866 |
| 9-middle | 0.296 | 0.005 | 0.174 | 0.007 | 0.034 | 0.000 | 0.000 | 0.013 | 0.530 |
| 9-outside | 0.274 | 0.004 | 0.278 | 0.006 | 0.021 | 0.000 | 0.000 | 0.023 | 0.605 |
| 10-inside | 1.760 | 0.071 | 0.898 | 0.058 | 0.370 | 0.001 | 0.066 | 0.225 | 3.449 |
| 10-middle | 0.389 | 0.019 | 0.243 | 0.018 | 0.096 | 0.016 | 0.016 | 0.048 | 0.844 |
| 10-outside | 0.192 | 0.003 | 0.042 | 0.003 | 0.019 | 0.000 | 0.000 | 0.015 | 0.274 |
| 11-inside | 0.935 | 0.028 | 0.215 | 0.027 | 0.196 | 0.038 | 0.038 | 0.026 | 1.504 |
| 11-middle | 0.648 | 0.025 | 0.430 | 0.003 | 0.000 | 0.001 | 0.013 | 0.006 | 1.127 |
| 11-outside | 0.215 | 0.004 | 0.107 | 0.007 | 0.000 | 0.000 | 0.001 | 0.019 | 0.353 |
| 12-inside | 2.683 | 0.182 | 1.297 | 0.674 | 0.001 | 0.001 | 0.088 | 0.133 | 5.060 |
| 12-middle | 0.812 | 0.038 | 0.533 | 0.021 | 0.001 | 0.018 | 0.019 | 0.003 | 1.445 |
| 12-outside | 0.737 | 0.023 | 0.528 | 0.025 | 0.001 | 0.009 | 0.004 | 0.037 | 1.363 |

Monoterpenes from SYP (loblolly) increment cores: February, 1998

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 1.867 | 0.100 | 1.107 | 0.089 | 0.325 | 0.021 | 0.023 | 0.049 | 3.581 |
| 1-middle | 0.711 | 0.026 | 0.443 | 0.032 | 0.090 | 0.008 | 0.008 | 0.026 | 1.345 |
| 1-outside | 0.430 | 0.007 | 0.108 | 0.008 | 0.012 | 0.000 | 0.000 | 0.016 | 0.582 |
| 2-inside | 2.103 | 0.083 | 1.311 | 0.080 | 0.379 | 0.029 | 0.028 | 0.118 | 4.131 |
| 2-middle | 1.181 | 0.065 | 0.777 | 0.081 | 0.159 | 0.001 | 0.002 | 0.076 | 2.342 |
| 2-outside | 0.634 | 0.010 | 0.129 | 0.010 | 0.018 | 0.000 | 0.000 | 0.019 | 0.819 |
| 3-inside | 0.733 | 0.029 | 0.125 | 0.011 | 0.142 | 0.022 | 0.022 | 0.023 | 1.106 |
| 3-middle | 0.697 | 0.039 | 0.391 | 0.023 | 0.191 | 0.029 | 0.028 | 0.040 | 1.439 |
| 3-outside | 0.397 | 0.007 | 0.110 | 0.008 | 0.043 | 0.000 | 0.000 | 0.021 | 0.585 |
| 4-inside | 1.726 | 0.075 | 0.462 | 0.050 | 0.582 | 0.063 | 0.061 | 0.076 | 3.096 |
| 4-middle | 0.415 | 0.034 | 0.256 | 0.029 | 0.273 | 0.033 | 0.033 | 0.058 | 1.131 |
| 4-outside | 0.341 | 0.007 | 0.127 | 0.007 | 0.023 | 0.000 | 0.000 | 0.022 | 0.526 |
| 5-inside | 1.142 | 0.050 | 0.528 | 0.030 | 0.271 | 0.048 | 0.046 | 0.033 | 2.148 |
| 5-middle | 0.259 | 0.005 | 0.236 | 0.008 | 0.034 | 0.001 | 0.000 | 0.014 | 0.557 |
| 5-outside | 0.228 | 0.004 | 0.134 | 0.006 | 0.012 | 0.000 | 0.000 | 0.018 | 0.402 |
| 6-inside | 1.061 | 0.019 | 0.292 | 0.022 | 0.233 | 0.002 | 0.002 | 0.023 | 1.656 |
| 6-middle | 0.459 | 0.009 | 0.158 | 0.013 | 0.121 | 0.000 | 0.000 | 0.026 | 0.787 |
| 6-outside | 0.277 | 0.005 | 0.082 | 0.007 | 0.058 | 0.000 | 0.000 | 0.028 | 0.456 |
| 7-inside | 1.485 | 0.067 | 0.117 | 0.057 | 0.793 | 0.027 | 0.030 | 0.088 | 2.663 |
| 7-middle | 0.542 | 0.034 | 0.088 | 0.037 | 0.434 | 0.009 | 0.011 | 0.055 | 1.209 |
| 7-outside | 0.393 | 0.007 | 0.024 | 0.010 | 0.117 | 0.000 | 0.000 | 0.026 | 0.577 |
| 8-inside | 1.948 | 0.085 | 0.562 | 0.067 | 0.414 | 0.087 | 0.085 | 0.087 | 3.336 |
| 8-middle | 0.668 | 0.044 | 0.099 | 0.020 | 0.101 | 0.033 | 0.033 | 0.047 | 1.045 |
| 8-outside | 0.343 | 0.005 | 0.034 | 0.006 | 0.024 | 0.000 | 0.000 | 0.017 | 0.430 |
| 9-inside | 1.594 | 0.065 | 1.014 | 0.052 | 0.281 | 0.029 | 0.034 | 0.098 | 3.168 |
| 9-middle | 0.670 | 0.031 | 0.499 | 0.028 | 0.096 | 0.008 | 0.010 | 0.046 | 1.387 |
| 9-outside | 0.341 | 0.005 | 0.139 | 0.007 | 0.026 | 0.000 | 0.000 | 0.047 | 0.567 |
| 10-inside | 1.396 | 0.066 | 0.621 | 0.042 | 0.258 | 0.043 | 0.043 | 0.173 | 2.643 |
| 10-middle | 0.495 | 0.025 | 0.178 | 0.016 | 0.086 | 0.019 | 0.019 | 0.069 | 0.906 |
| 10-outside | 0.213 | 0.003 | 0.060 | 0.004 | 0.013 | 0.000 | 0.000 | 0.026 | 0.318 |
| 11-inside | 1.262 | 0.040 | 0.604 | 0.031 | 0.170 | 0.031 | 0.031 | 0.043 | 2.212 |
| 11-middle | 0.741 | 0.039 | 0.643 | 0.030 | 0.139 | 0.028 | 0.028 | 0.042 | 1.688 |
| 11-outside | 0.273 | 0.005 | 0.152 | 0.009 | 0.042 | 0.000 | 0.000 | 0.022 | 0.502 |
| 12-inside | 3.710 | 0.232 | 0.979 | 0.165 | 0.678 | 0.083 | 0.088 | 0.158 | 6.093 |
| 12-middle | 0.729 | 0.028 | 0.269 | 0.018 | 0.070 | 0.022 | 0.025 | 0.019 | 1.180 |
| 12-outside | 0.655 | 0.040 | 0.635 | 0.053 | 0.162 | 0.015 | 0.015 | 0.065 | 1.641 |

**Monoterpenes from SYP (loblolly) increment cores: March, 1998**

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 1.473 | 0.108 | 1.150 | 0.099 | 0.816 | 0.012 | 0.037 | 0.092 | 3.787 |
| 1-middle | 0.412 | 0.020 | 0.288 | 0.026 | 0.126 | 0.007 | 0.007 | 0.025 | 0.910 |
| 1-outside | 0.180 | 0.003 | 0.045 | 0.003 | 0.005 | 0.000 | 0.000 | 0.006 | 0.242 |
| 2-inside | 1.631 | 0.069 | 1.003 | 0.063 | 0.334 | 0.031 | 0.030 | 0.103 | 3.264 |
| 2-middle | 0.336 | 0.010 | 0.143 | 0.010 | 0.021 | 0.000 | 0.000 | 0.019 | 0.540 |
| 2-outside | 0.202 | 0.004 | 0.045 | 0.004 | 0.007 | 0.000 | 0.000 | 0.007 | 0.268 |
| 3-inside | 0.751 | 0.026 | 0.168 | 0.014 | 0.134 | 0.020 | 0.021 | 0.173 | 1.306 |
| 3-middle | 0.348 | 0.015 | 0.254 | 0.015 | 0.081 | 0.011 | 0.011 | 0.020 | 0.756 |
| 3-outside | 0.218 | 0.005 | 0.074 | 0.006 | 0.027 | 0.000 | 0.000 | 0.012 | 0.342 |
| 4-inside | 1.093 | 0.088 | 0.429 | 0.053 | 0.607 | 0.069 | 0.066 | 0.086 | 2.492 |
| 4-middle | 0.291 | 0.010 | 0.102 | 0.008 | 0.059 | 0.006 | 0.006 | 0.020 | 0.502 |
| 4-outside | 0.201 | 0.004 | 0.077 | 0.005 | 0.018 | 0.000 | 0.000 | 0.013 | 0.318 |
| 5-inside | 0.772 | 0.036 | 0.383 | 0.021 | 0.191 | 0.035 | 0.033 | 0.027 | 1.499 |
| 5-middle | 0.141 | 0.002 | 0.116 | 0.004 | 0.015 | 0.000 | 0.000 | 0.010 | 0.287 |
| 5-outside | 0.152 | 0.002 | 0.084 | 0.003 | 0.008 | 0.000 | 0.000 | 0.010 | 0.260 |
| 6-inside | 0.694 | 0.011 | 0.175 | 0.013 | 0.139 | 0.001 | 0.001 | 0.015 | 1.049 |
| 6-middle | 0.304 | 0.011 | 0.141 | 0.010 | 0.098 | 0.002 | 0.002 | 0.037 | 0.605 |
| 6-outside | 0.133 | 0.002 | 0.038 | 0.003 | 0.024 | 0.000 | 0.000 | 0.015 | 0.216 |
| 7-inside | 1.545 | 0.144 | 0.338 | 0.133 | 1.626 | 0.046 | 0.050 | 0.159 | 4.040 |
| 7-middle | 0.216 | 0.009 | 0.011 | 0.006 | 0.085 | 0.005 | 0.005 | 0.010 | 0.346 |
| 7-outside | 0.157 | 0.003 | 0.014 | 0.004 | 0.041 | 0.000 | 0.000 | 0.009 | 0.229 |
| 8-inside | 1.870 | 0.142 | 0.726 | 0.085 | 0.545 | 0.110 | 0.102 | 0.098 | 3.678 |
| 8-middle | 0.290 | 0.018 | 0.063 | 0.009 | 0.045 | 0.012 | 0.012 | 0.024 | 0.472 |
| 8-outside | 0.142 | 0.002 | 0.015 | 0.003 | 0.010 | 0.000 | 0.000 | 0.009 | 0.180 |
| 9-inside | 1.843 | 0.117 | 1.408 | 0.097 | 0.632 | 0.051 | 0.057 | 0.163 | 4.367 |
| 9-middle | 0.325 | 0.016 | 0.281 | 0.014 | 0.050 | 0.006 | 0.007 | 0.022 | 0.721 |
| 9-outside | 0.163 | 0.003 | 0.072 | 0.004 | 0.015 | 0.000 | 0.000 | 0.018 | 0.274 |
| 10-inside | 1.294 | 0.087 | 0.414 | 0.043 | 0.328 | 0.055 | 0.073 | 0.168 | 2.462 |
| 10-middle | 0.359 | 0.014 | 0.126 | 0.009 | 0.045 | 0.008 | 0.008 | 0.036 | 0.605 |
| 10-outside | 0.160 | 0.002 | 0.042 | 0.003 | 0.010 | 0.000 | 0.000 | 0.011 | 0.227 |
| 11-inside | 1.127 | 0.048 | 0.810 | 0.032 | 0.177 | 0.036 | 0.036 | 0.057 | 2.323 |
| 11-middle | 0.265 | 0.008 | 0.147 | 0.008 | 0.044 | 0.004 | 0.004 | 0.016 | 0.496 |
| 11-outside | 0.132 | 0.002 | 0.074 | 0.004 | 0.019 | 0.000 | 0.000 | 0.015 | 0.245 |
| 12-inside | 1.606 | 0.138 | 0.632 | 0.093 | 0.364 | 0.058 | 0.064 | 0.100 | 3.054 |
| 12-middle | 0.607 | 0.042 | 0.364 | 0.025 | 0.075 | 0.016 | 0.017 | 0.039 | 1.185 |
| 12-outside | 0.289 | 0.014 | 0.188 | 0.011 | 0.043 | 0.001 | 0.008 | 0.028 | 0.580 |

**Monoterpenes from SYP (loblolly) increment cores: April, 1998**

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 0.965 | 0.037 | 0.446 | 0.029 | 0.183 | 0.016 | 0.122 | 0.036 | 1.854 |
| 1-middle | 0.398 | 0.025 | 0.245 | 0.046 | 0.045 | 0.002 | 0.002 | 0.013 | 0.776 |
| 1-outside | 0.174 | 0.003 | 0.045 | 0.073 | 0.005 | 0.000 | 0.000 | 0.005 | 0.306 |
| 2-inside | 1.486 | 0.068 | 1.065 | 0.005 | 0.287 | 0.029 | 0.204 | 0.091 | 3.235 |
| 2-middle | 0.271 | 0.010 | 0.155 | 0.058 | 0.023 | 0.000 | 0.000 | 0.020 | 0.538 |
| 2-outside | 0.241 | 0.004 | 0.064 | 0.078 | 0.008 | 0.000 | 0.000 | 0.009 | 0.404 |
| 3-inside | 1.547 | 0.045 | 0.705 | 0.004 | 0.228 | 0.019 | 0.162 | 0.042 | 2.752 |
| 3-middle | 0.313 | 0.017 | 0.232 | 0.066 | 0.087 | 0.005 | 0.002 | 0.019 | 0.740 |
| 3-outside | 0.170 | 0.003 | 0.055 | 0.055 | 0.022 | 0.000 | 0.000 | 0.009 | 0.314 |
| 4-inside | 0.927 | 0.071 | 0.365 | 0.063 | 0.469 | 0.061 | 0.043 | 0.078 | 2.076 |
| 4-middle | 0.210 | 0.004 | 0.076 | 0.056 | 0.020 | 0.000 | 0.004 | 0.013 | 0.382 |
| 4-outside | 0.184 | 0.003 | 0.066 | 0.072 | 0.009 | 0.000 | 0.000 | 0.009 | 0.343 |
| 5-inside | 0.253 | 0.005 | 0.189 | 0.046 | 0.035 | 0.003 | 0.035 | 0.008 | 0.573 |
| 5-middle | 0.147 | 0.002 | 0.117 | 0.067 | 0.024 | 0.000 | 0.000 | 0.006 | 0.363 |
| 5-outside | 0.140 | 0.002 | 0.090 | 0.056 | 0.008 | 0.000 | 0.000 | 0.008 | 0.304 |
| 6-inside | 0.631 | 0.014 | 0.176 | 0.006 | 0.107 | 0.003 | 0.028 | 0.030 | 0.995 |
| 6-middle | 0.221 | 0.003 | 0.058 | 0.001 | 0.077 | 0.000 | 0.002 | 0.020 | 0.383 |
| 6-outside | 0.083 | 0.001 | 0.014 | 0.000 | 0.010 | 0.000 | 0.000 | 0.006 | 0.114 |
| 7-inside | 0.845 | 0.066 | 0.078 | 0.124 | 0.394 | 0.034 | 0.010 | 0.057 | 1.608 |
| 7-middle | 0.213 | 0.008 | 0.016 | 0.007 | 0.117 | 0.000 | 0.000 | 0.012 | 0.372 |
| 7-outside | 0.193 | 0.003 | 0.011 | 0.003 | 0.043 | 0.000 | 0.000 | 0.009 | 0.262 |
| 8-inside | 1.410 | 0.089 | 0.611 | 0.024 | 0.259 | 0.070 | 0.008 | 0.058 | 2.530 |
| 8-middle | 0.202 | 0.004 | 0.016 | 0.000 | 0.000 | 0.000 | 0.000 | 0.012 | 0.235 |
| 8-outside | 0.198 | 0.002 | 0.016 | 0.000 | 0.011 | 0.000 | 0.000 | 0.012 | 0.238 |
| 9-inside | 1.212 | 0.056 | 0.929 | 0.007 | 0.409 | 0.032 | 0.007 | 0.081 | 2.735 |
| 9-middle | 0.214 | 0.006 | 0.122 | 0.000 | 0.000 | 0.000 | 0.000 | 0.013 | 0.356 |
| 9-outside | 0.156 | 0.002 | 0.068 | 0.000 | 0.015 | 0.000 | 0.000 | 0.017 | 0.259 |
| 10-inside | 0.965 | 0.047 | 0.170 | 0.008 | 0.166 | 0.043 | 0.001 | 0.098 | 1.498 |
| 10-middle | 0.255 | 0.010 | 0.110 | 0.000 | 0.030 | 0.005 | 0.004 | 0.027 | 0.441 |
| 10-outside | 0.122 | 0.002 | 0.052 | 0.000 | 0.007 | 0.000 | 0.000 | 0.011 | 0.194 |
| 11-inside | 1.102 | 0.036 | 0.616 | 0.003 | 0.092 | 0.026 | 0.020 | 0.032 | 1.928 |
| 11-middle | 0.201 | 0.008 | 0.279 | 0.022 | 0.024 | 0.004 | 0.005 | 0.013 | 0.555 |
| 11-outside | 0.138 | 0.002 | 0.113 | 0.000 | 0.019 | 0.000 | 0.000 | 0.013 | 0.285 |
| 12-inside | 1.294 | 0.068 | 0.407 | 0.003 | 0.158 | 0.033 | 0.005 | 0.047 | 2.015 |
| 12-middle | 0.444 | 0.034 | 0.388 | 0.033 | 0.079 | 0.009 | 0.012 | 0.028 | 1.027 |
| 12-outside | 0.286 | 0.013 | 0.247 | 0.008 | 0.038 | 0.005 | 0.005 | 0.024 | 0.626 |

**Monoterpenes from SYP (loblolly) increment cores: May, 1998**

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 2.631 | 0.154 | 1.518 | 0.023 | 0.734 | no data | 0.015 | 0.531 | 5.606 |
| 1-middle | 0.182 | 0.003 | 0.029 | 0.002 | 0.007 | no data | 0.001 | 0.005 | 0.230 |
| 1-outside | 0.752 | 0.064 | 0.397 | 0.041 | 0.109 | no data | 0.003 | 0.059 | 1.425 |
| 2-inside | 1.545 | 0.079 | 1.177 | 0.008 | 0.481 | no data | 0.000 | 0.320 | 3.611 |
| 2-middle | 0.245 | 0.009 | 0.109 | 0.012 | 0.023 | no data | 0.011 | 0.012 | 0.420 |
| 3-inside | 0.737 | 0.025 | 0.203 | 0.004 | 0.127 | no data | 0.020 | 0.002 | 1.119 |
| 4-inside | 2.460 | 0.186 | 1.032 | 0.094 | 1.362 | no data | 0.002 | 1.109 | 6.244 |
| 5-inside | 0.611 | 0.016 | 0.493 | 0.001 | 0.114 | no data | 0.001 | 0.121 | 1.356 |
| 6-inside | 0.798 | 0.017 | 0.219 | 0.076 | 0.160 | no data | 0.034 | 0.034 | 1.339 |
| 7-inside | 1.242 | 0.078 | 0.000 | 0.184 | 0.139 | no data | 0.016 | 0.238 | 1.897 |
| 8-inside | 2.467 | 0.115 | 0.807 | 0.058 | 0.134 | no data | 0.071 | 0.587 | 4.240 |
| 8-middle | 0.102 | 0.002 | 0.007 | 0.009 | 0.029 | no data | 0.000 | 0.002 | 0.151 |
| 8-outside | 0.118 | 0.002 | 0.010 | 0.002 | 0.030 | no data | 0 | 0 | 0.162 |
| 9-inside | 1.497 | 0.072 | 1.024 | 0.057 | 0.048 | no data | 0.030 | 0.197 | 2.925 |
| 9-outside | 0.216 | 0.006 | 0.134 | 0.005 | 0.008 | no data | 0.000 | 0.001 | 0.370 |
| 10-middle | 0.139 | 0.000 | 0.116 | 0.007 | 0 | no data | 0.172 | 0.376 | 0.810 |
| 11-inside | 0.451 | 0.024 | 0.106 | 0.002 | 0.156 | no data | 0.002 | 0 | 0.742 |
| 11-middle | 0.083 | 0.002 | 0.013 | 0.000 | 0.004 | no data | 0 | 0.006 | 0.108 |
| 12-inside | 0.451 | 0.070 | 0.075 | 0.008 | 0.305 | no data | 0.001 | 0.100 | 1.009 |
| 12-outside | 0.115 | 0.003 | 0.057 | 0 | 0.004 | no data | 0.001 | 0.002 | 0.184 |

The following May 1998 data were not considered due to experimental/instrument problems:

**Monoterpenes from SYP (loblolly) increment cores: May, 1998 (bad analyses)**

*Concentration (g/g OD wood, %)*

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 2-outside | 0.000 | 0 | 0 | 0 | 0 | no data | 0 | 0 | 0.000 |
| 3-middle | 0.034 | 0.001 | 0.005 | 0.002 | 0.002 | no data | 0 | 0.000 | 0.044 |
| 3-outside | 0 | 0.008 | 0 | 0 | 0.000 | no data | 0 | 0 | 0.008 |
| 4-middle | 0.001 | 0 | 0 | 0 | 0 | no data | 0 | 0 | 0.001 |
| 4-outside | 0.033 | 0.000 | 0.009 | 0.007 | 0.001 | no data | 0 | 0.000 | 0.051 |
| 5-middle | 0.027 | 0.000 | 0.021 | 0.005 | 0.002 | no data | 0 | 0.000 | 0.056 |
| 5-outside | 0.028 | 0.000 | 0.015 | 0.006 | 0.001 | no data | 0 | 0.000 | 0.051 |
| 6-middle | 0.026 | 0.000 | 0.020 | 0.004 | 0.002 | no data | 0 | 0.000 | 0.052 |
| 6-outside | 0.009 | 0 | 0.001 | 0.001 | 0.000 | no data | 0 | 0 | 0.012 |
| 7-middle | 0.001 | 0 | 0 | 0 | 0 | no data | 0 | 0 | 0.001 |
| 7-outside | 0.034 | 0.000 | 0.002 | 0.000 | 0.007 | no data | 0 | 0 | 0.043 |
| 9-middle | 0.054 | 0.001 | 0.002 | 0.002 | 0.001 | no data | 0 | 0.001 | 0.062 |
| 10-outside | 0.037 | 0 | 0.008 | 0.000 | 0.013 | no data | 0 | 0 | 0.057 |
| 11-outside | 0.043 | 0.001 | 0.013 | 0 | 0.006 | no data | 0 | 0.002 | 0.066 |
| 12-middle | 0.011 | 0.000 | 0.004 | 0 | 0.001 | no data | 0 | 0.000 | 0.016 |

**Monoterpenes from SYP (loblolly) increment cores: June, 1998**

***Concentration (g/g OD wood, %)***

| Sample | a-Pinene | Camphene | b-Pinene | Myrcene | Limonene | Fenchyl alcohol | Borneol | 4-allyl-anisole | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1-inside | 1.754 | 0.123 | 1.085 | 0.145 | 0.553 | 0.041 | 0.043 | 0.060 | 3.804 |
| 1-middle | 0.373 | 0.022 | 0.251 | 0.084 | 0.110 | 0.007 | 0.008 | 0.014 | 0.868 |
| 1-outside | 0.168 | 0.003 | 0.058 | 0.004 | 0.051 | 0.000 | 0.000 | 0.005 | 0.289 |
| 2-inside | 1.461 | 0.071 | 0.906 | 0.065 | 0.248 | 0.014 | 0.015 | 0.094 | 2.875 |
| 2-middle | 0.253 | 0.010 | 0.153 | 0.067 | 0.024 | 0.000 | 0.000 | 0.019 | 0.526 |
| 2-outside | 0.154 | 0.003 | 0.044 | 0.004 | 0.048 | 0.000 | 0.000 | 0.007 | 0.260 |
| 3-inside | 0.744 | 0.024 | 0.173 | 0.078 | 0.116 | 0.019 | 0.021 | 0.019 | 1.194 |
| 3-middle | 0.138 | 0.009 | 0.092 | 0.051 | 0.038 | 0.006 | 0.007 | 0.009 | 0.349 |
| 3-outside | 0.119 | 0.002 | 0.043 | 0.003 | 0.033 | 0.000 | 0.000 | 0.007 | 0.206 |
| 4-inside | 1.001 | 0.066 | 0.424 | 0.071 | 0.499 | 0.055 | 0.056 | 0.079 | 2.250 |
| 4-middle | 0.359 | 0.021 | 0.264 | 0.077 | 0.129 | 0.009 | 0.009 | 0.040 | 0.906 |
| 4-outside | 0.148 | 0.003 | 0.062 | 0.003 | 0.047 | 0.000 | 0.000 | 0.007 | 0.271 |
| 5-inside | 0.635 | 0.020 | 0.608 | 0.068 | 0.159 | 0.022 | 0.021 | 0.018 | 1.551 |
| 5-middle | 0.144 | 0.002 | 0.146 | 0.091 | 0.025 | 0.000 | 0.000 | 0.007 | 0.417 |
| 5-outside | 0.164 | 0.003 | 0.114 | 0.004 | 0.066 | 0.000 | 0.000 | 0.010 | 0.361 |
| 6-inside | 1.000 | 0.029 | 0.282 | 0.103 | 0.228 | 0.009 | 0.011 | 0.066 | 1.729 |
| 6-middle | 0.159 | 0.005 | 0.055 | 0.064 | 0.050 | 0.002 | 0.002 | 0.013 | 0.352 |
| 6-outside | 0.135 | 0.002 | 0.036 | 0.003 | 0.044 | 0.000 | 0.000 | 0.008 | 0.229 |
| 7-inside | 1.045 | 0.046 | 0.042 | 0.158 | 0.010 | 0.023 | 0.027 | 0.032 | 1.383 |
| 7-middle | 0.221 | 0.010 | 0.018 | 0.084 | 0.134 | 0.004 | 0.005 | 0.017 | 0.493 |
| 7-outside | 0.116 | 0.002 | 0.012 | 0.003 | 0.066 | 0.000 | 0.000 | 0.006 | 0.205 |
| 8-inside | 0.917 | 0.049 | 0.132 | 0.082 | 0.132 | 0.038 | 0.037 | 0.046 | 1.433 |
| 8-middle | 0.198 | 0.008 | 0.044 | 0.061 | 0.033 | 0.002 | 0.002 | 0.022 | 0.369 |
| 8-outside | 0.132 | 0.002 | 0.014 | 0.003 | 0.048 | 0.000 | 0.000 | 0.011 | 0.209 |
| 9-inside | 1.420 | 0.119 | 1.115 | 0.061 | 0.557 | 0.042 | 0.048 | 0.199 | 3.561 |
| 9-middle | 0.440 | 0.060 | 0.327 | 0.039 | 0.222 | 0.006 | 0.020 | 0.145 | 1.259 |
| 9-outside | 0.126 | 0.002 | 0.053 | 0.003 | 0.036 | 0.000 | 0.000 | 0.017 | 0.236 |
| 10-inside | 0.959 | 0.073 | 0.162 | 0.043 | 0.202 | 0.065 | 0.062 | 0.105 | 1.670 |
| 10-middl | 0.232 | 0.011 | 0.089 | 0.106 | 0.044 | 0.009 | 0.009 | 0.028 | 0.527 |
| 10-outsid | 0.158 | 0.002 | 0.040 | 0.002 | 0.072 | 0.000 | 0.000 | 0.010 | 0.284 |
| 11-inside | 0.916 | 0.033 | 0.423 | 0.010 | 0.098 | 0.024 | 0.027 | 0.021 | 1.551 |
| 11-middl | 0.434 | 0.024 | 0.412 | 0.143 | 0.111 | 0.013 | 0.012 | 0.080 | 1.229 |
| 11-outsid | 0.098 | 0.001 | 0.056 | 0.003 | 0.050 | 0.000 | 0.000 | 0.012 | 0.220 |
| 12-inside | 1.706 | 0.139 | 0.498 | 0.084 | 0.281 | 0.061 | 0.070 | 0.092 | 2.932 |
| 12-middl | 0.513 | 0.066 | 0.319 | 0.094 | 0.165 | 0.002 | 0.005 | 0.050 | 1.216 |
| 12-outsid | 0.251 | 0.015 | 0.265 | 0.019 | 0.051 | 0.013 | 0.012 | 0.041 | 0.668 |