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Low VOC Drying of Lumber and Wood Panel Products

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DISCLAIMER

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Abstract

Heating softwood in a low-headspace environment draws out the VOCs from the wood, without removing the water. The VOCs can be collected from the headspace, and represent a valuable product. The VOC-depleted wood can then be dried conventionally with much reduced emissions. Heating can be accomplished through radiofrequency (RF) or steam. For lumber, steam is inefficient, but brief RF treatment under low-headspace conditions draws out 80% of the VOCs. The power used is quite low, since the RF energy is not used to remove water, but only to maintain the wood at a set temperature. The technology is now at the pre-pilot stage. Either steam or RF can be used for particle, OSB, and veneer, again under low-headspace conditions. Increasing steam temperature facilitates VOC removal. In order to understand the mechanism of VOC release in lumber, the transport of water and VOCs to the surface is being studied as a function of sample size and orientation. Characterization of the terpenes and resin/fatty acids from a control set of trees is underway in order to define the seasonal influence on VOCs.

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. The headspace is too small to accommodate the water, but is large enough to hold the VOCs. 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). Four furnishes: lumber, OSB, sawdust, and veneer were used, the mode of heating most appropriate to each was identified, and methods for collecting the headspace VOCs were developed. 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.

STUDIES ON LUMBER

Low headspace drying under steam (MSU)

In order to evaluate the feasibility of removing VOCs from lumber by steaming it in a low headspace environment, one of the experimental pilot-scale kilns at MSU was fitted with a steam spray. Two kiln runs were made with matched samples of Southern pine cut end to end. Three cu ft of wood with an average specific gravity was 0.42 were used for each run. One set was steamed for 5 hours (under saturation conditions) in a 14.8 cu ft. steamer, and then kiln-dried for 18 hours in a 11.7 cu ft. dryer. The other served as a control and was kiln-dried for 18 hours. Steaming was done at 212°F, the kiln temperature was 245°F, and the wet-bulb temperature during drying was approximately 180°F, but was not controlled. Total hydrocarbon data was collected throughout the entire drying cycle, and are illustrated in Figure 1. Emissions from the control lumber, were 3.7 pounds/dry ton; those from the pre-steamed and then kiln-dried material were 3.3 pounds/dry ton, i.e. steaming removed about 10% of the total VOCs. The final moisture content of the lumber was 6% on an oven-dry basis.

The level of VOC emissions from the control material was typical, with the emission surges occurring when expected. The initial surge was missing for the steamed lumber, suggesting that this material was removed during steaming. The profile from the control essentially lagged that of the steamed material by about 2 hours.

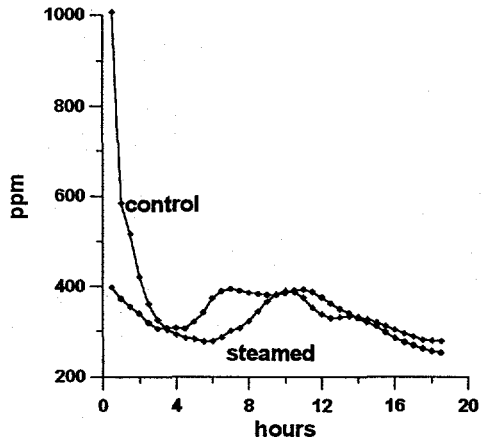

Figure 1: VOCs from steamed and control flakes

In order to confirm these results, green 2" x 6" yellow pine of specific gravity 0.42-0.44 was cut to 23" lengths and divided into matched charges, each containing about 3 cu ft of wood, which corresponds to 18 boards. The boards were dried at 245°F dry bulb temperature for 18 hours. The control was dried on 10.2.96, and its matched pair was steamed for 5 hours prior to drying on 10.3.96. Total hydrocarbon emission data are illustrated in Table 1 and Figure 2. The emission rates were similar to those from other charges dried previously under similar conditions. Again, steaming lowered the total hydrocarbon emissions, but only by 0.16 lbs per dry ton of wood.

In order to determine the influence of wood geometry on emissions, lumber was cut to 6" lengths and divided into matched charges, each containing 61 pieces. The total wood volume in each of these charges was approximately 2.54 cu ft. The control was dried for 18 hours at 245°F dry bulb temperature on 10.8.96; the other charge was steamed for 5 hours at approximately 212°F prior to drying on 10.9.96. As shown in Table 1 and illustrated in Figure 3, emissions from the 6" control were much higher than those from the 23" material, indicating that end effects are substantial. VOCs from the steamed 6" charge were substantially lower than those from either the control or the steamed 23" charge, suggesting that steam extraction works best for small pieces of wood. Hence, steaming alone is not useful for lumber, but should work well for particle and OSB.

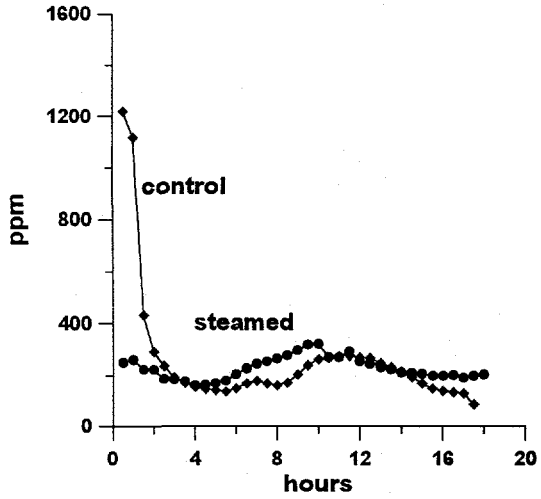

Figure 2: VOCs from 23" lengths

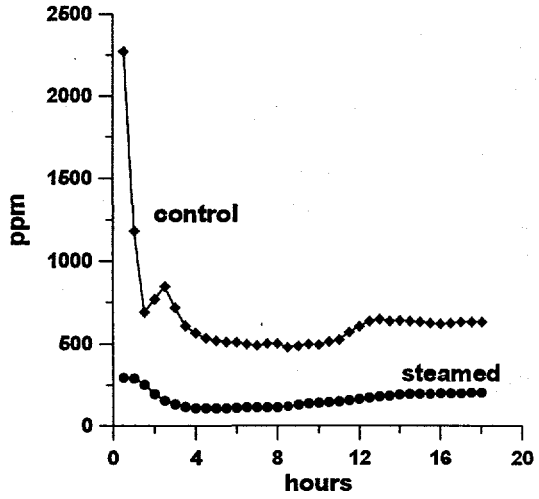

Figure 3: VOCs from 6" lengths

Table 1: VOC emissions from lumber					
charge	$W_{initial}$ (lbs.)	$W_{post\text{-}steam}$ (lbs.)	W_{final} (lbs.)	MC_{final} (%)	VOC (lbs./dry ton)
23" (control)	165		73.5	6	2.81
23" (steamed)	164	160	70.5	6	2.65
6" (control)	152		69	5	7.39
6" (steamed)	148	142	66	5	1.92

Effect of RF pre-heating on VOC emissions (IPST/MSU)

Although steam is able to extract VOCs from lumber, the rate of extraction is too slow to be of commercial use. RF seemed to offer an alternative, since, unlike steam, RF heats from the inside out. Accordingly, measurements were made with lumber placed in a low-headspace configuration, and irradiated at 27.12 MHz with the Strayfield RF dryer at Georgia Power's Technology Application Center in Atlanta. A schematic of the dryer is provided in Figure 4. The gap between the two plates was set at 7 inches, and the irradiation intensity was controlled through the current applied.

Irradiation of plastic-wrapped lumber at 1amp

Preliminary work was done with lumber wrapped in plastic to simulate a low headspace. Yellow pine boards obtained locally as rough, green, 2" x 10" and 2" x 12" samples were ripped lengthwise to final widths of 4.75" and 3.5", respectively, and to a length of 24". Two matched sets were prepared from each board. One board from each set was shipped to Atlanta for RF treatment. The matching pair was wrapped in polyethylene and stored at 2°C at MSU for two weeks until the treated wood was returned from Atlanta. Both samples were then dried at MSU at the same kiln schedule of 245°F dry bulb temperature for 18 hours. The wet bulb temperature was not regulated.

Two pieces of plastic-wrapped lumber were irradiated, the larger piece for 220 seconds and the smaller one for 120 seconds. Both pieces were then dried together. VOC and weight loss data are provided in Table 2, and the VOC profiles are illustrated in Figure 5. The RF-treated lumber emitted considerably less VOC than did the control. Ideally, VOC loss should be maximal, and water loss, minimal, since evaporation with RF is power-intensive. Since some water was lost during irradiation, the measurements were repeated at lower RF power in order to retain more of the water inside the wood.

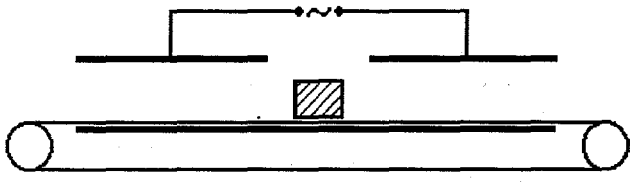

Figure 4: Schematic of the Strayfield RF dryer

Table 2: VOC emissions from lumber irradiated at 1A

charge	$W_{initial}$ (lbs.)	$W_{post\text{-}RF}$ (lbs.)	W_{final} (lbs.)	MC_{final} (%)	emissions (lb./dry ton)
RF-treated	12.84	11.01	6.42	3	1.01
control	12.16		6.12	3	1.65

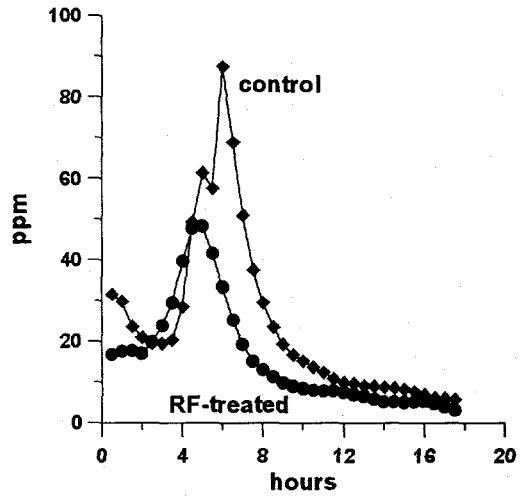

Figure 5: Comparison of VOCs from RF-treated (1A) and control lumber

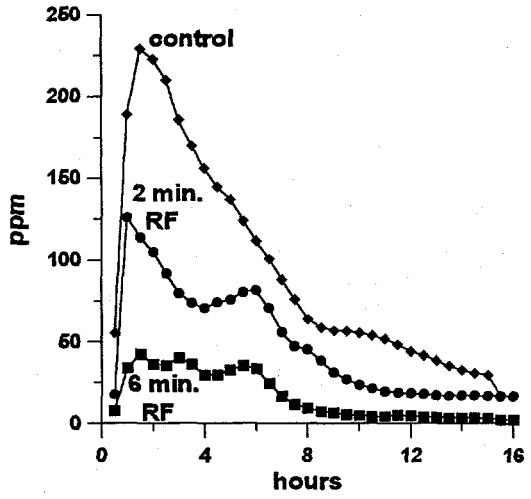

Figure 6: Comparison of VOCs from RF-treated (0.6A) and control lumber

Irradiation of plastic-wrapped lumber at 0.6 amps

Three matched charges of wood were prepared; each contained two (1.75" x 3.5" x 23") boards. Two of these charges were wrapped in plastic and irradiated for 2 min. and 6 min. respectively with an applied current of 0.6A. The third served as a control. All three charges were then dried at MSU's pilot kiln. Moisture and VOC data are listed in Table 3, and the VOC profiles are illustrated in Figure 6. The results are very encouraging in that 49% of the VOCs was removed in the 2-minute treatment with essentially no loss of water. About 63% of the VOCs were removed during the 6-min RF treatment, but 25% of the available water was also lost. We, therefore, have the option of losing a substantial fraction of the VOC with very little power consumption, or much more VOC with higher power consumption. The trade-off will be dictated by the relative costs of power and control devices.

Table 3: VOC emissions from lumber irradiated at 0.6A

RF time (min.)	$W_{initial}$ (lbs.)	$W_{post\text{-}RF}$ (lbs.)	W_{final} (lbs.)	$MC_{initial}$ (%)	$MC_{post\text{-}RF}$ (%)	MC_{final} (%)	VOC (lbs. per dry ton)
0 (control)	10.24		5.04	103.2		0	2.86
2	10.02	9.93	5.03	99.2	97.4	0	1.46
6	8.68	7.79	4.79	81.2	62.6	0	1.05

MSU's kiln is too small to accommodate commercial 2 in x 4 in x 48 in sizes, and samples are split in half prior to drying. The question then arises as to whether VOC extraction with RF would also work with commercial-size samples. To simulate larger samples, freshly cut commercial 2 in x 4 in x 23 in pieces of lumber were dipped in melted paraffin to seal the end grain, and each piece was then wrapped in polyethylene film for RF treatment. One cut section was set aside as a control, and the other irradiated at Georgia Power, at a power level of 0.8 A for 6, 10, and 20 minutes. The irradiated samples were then dried at MSU, and the emissions are provided in

Table 4: VOCs from end-sealed lumber				
run	initial MC[1]	final MC[1]	RF treatment time (min)	VOC (lbs per dry ton)
011397-A-011397-D	108	6	0	3.08
011397-AA	105	0	6	2.11
011397-BB	88.9	0	10	2.19
011397-CC	60.9	0	20	0.97
[1]MC: dry basis moisture content (percent)				

Table 4. The control (un-irradiated) samples were dried as a group, since no major differences were expected among them. The Table 4 results confirm our previous findings that RF removes VOCs even from these partially sealed samples. Hence, low-headspace RF should be able to extract VOCs from commercial sizes of lumber.

Unit for low-headspace RF-induced VOC extraction

Having proved feasibility with the plastic-wrapped lumber, we now constructed the low-headspace extraction vessel shown in Figure 7. The unit is a 1.2 m long by 11.4 cm OD polyethylene tube with a polyethylene flange heat-welded at one end, and a plate welded at the opposite end. Teflon shutoff valves were installed at both ends. A trap containing water was connected to one end of the extraction vessel. Fiberglass thermocouples were used to determine the surface and internal temperatures of the board during irradiation. The internal temperature was obtained by inserting the thermocouple into a pre-drilled hole in the lumber which reached the board center-line. Four experiments were conducted on 2" x 3.75" x 48" pine boards as follows:

- 30 minutes of continuous RF treatment at 0.8 amps;
- 30 minutes of intermittent RF treatment at 1.1 amps with the power being manually cycled on and off to maintain the surface temperature at about 90°C;
- repetition of the above treatment for 15 minutes;
- RF treatment until pressure build-up in the vessel indicating the release of steam.

Table 5 presents the summary of the RF treatment experiments. The *RF time* reflects the irradiation time; the *total time* includes the additional time the wood was in the cylinder, regardless of whether or not the RF unit was on. The temperature profiles of the various experiments are shown in Figures 8-11. The VOC profiles are illustrated in Figure 12.

Entries 4-21-97-F and 4-21-97-H in Table 5 received the same amount of radiation, but the former was kept in the unit for a longer period, and the wood was exposed to saturated headspace conditions for a longer period. Not surprisingly, increasing power (comparison of 4-21-97-C and 4-21-97-F) and exposure period (4-21-97-H and 4-21-97-A) increased the amount of VOC removed. VOC reduction of 79% was observed in the best case (4-21-97-F). Importantly, this was achieved with minimal water loss, which opens the prospect of being able to drive out and collect the VOCs through low-headspace RF treatment, and to then dry the wood conventionally with much lower releases. The power requirement should be quite low since the RF field is *not* used to evaporate water, but only to maintain the wood at a set temperature.

Table 5: VOCs from RF-treated wood [1]				
ID	**weight loss (%)**	**VOC (lbs/ton)**	**RF power (amp)**	**RF time/total time (min)**
control	na	3.69	na	0
4-21-97-C	2.8	1.67	0.8	30/30
4-21-97-F	4.0	0.77	1.1	12/30
4-21-97-H	3.8	1.81	1.1	12/15
4-21-97-A	2.2	2.27	1.1	9/9
[1]green basis				

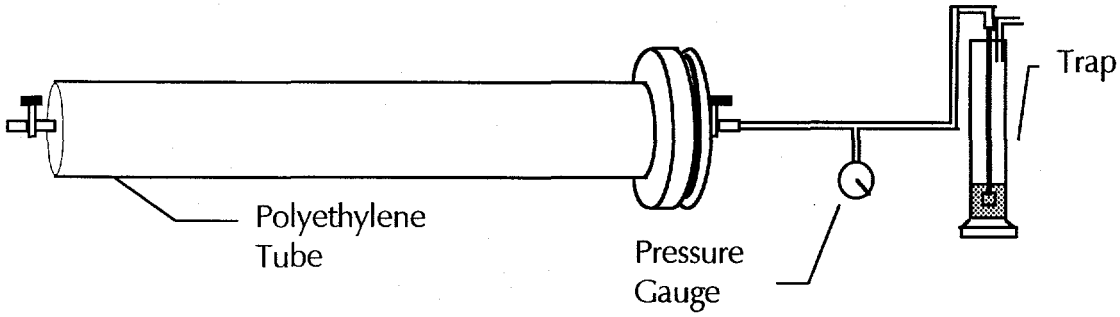

Figure 7: Schematic of RF VOC extraction vessel.

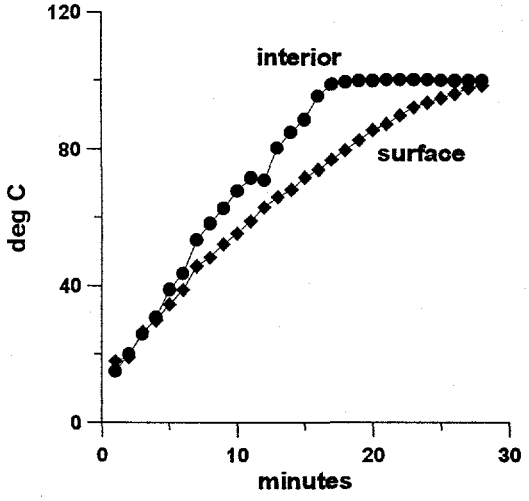

Figure 8: Temperature profiles in wood (4-21-97-C)

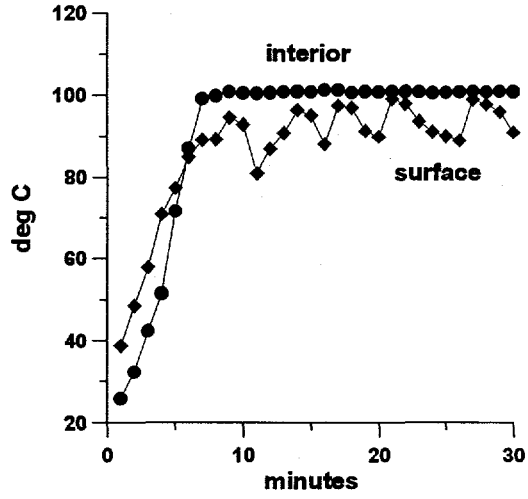

Figure 9: Temperature profiles in wood (4-21-97-F)

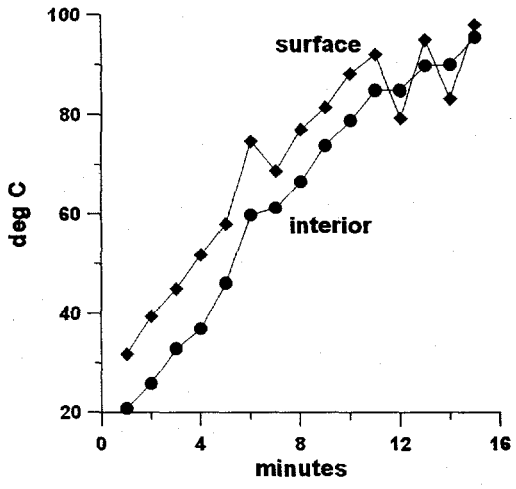

Figure 10: Temperature profiles in wood (4-21-97-H)

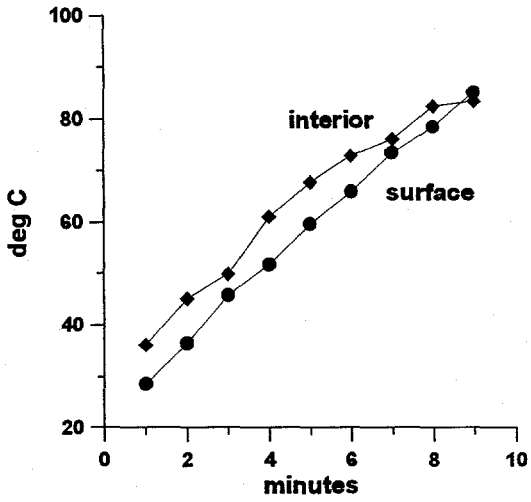

Figure 11: Temperature profiles in wood (4-21-97-A)

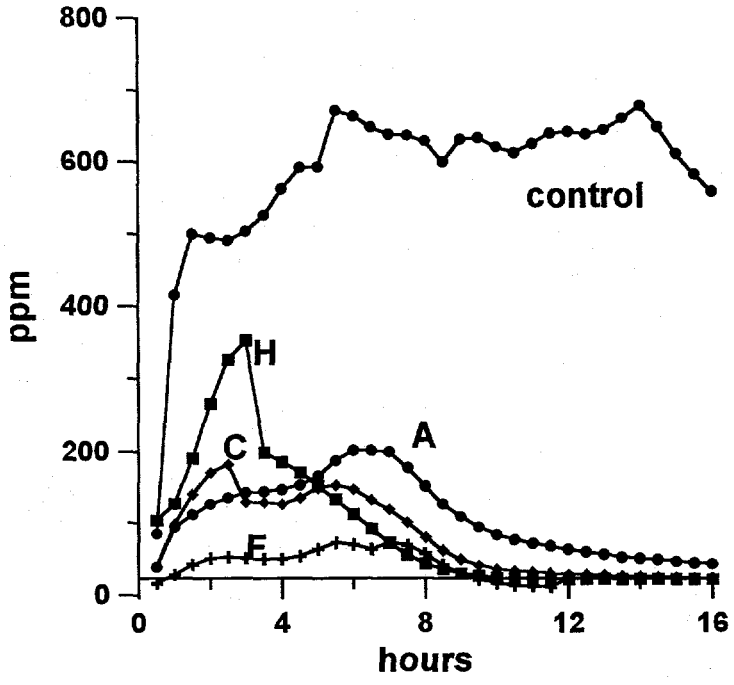

Figure 12: VOCs from low-headspace RF-treated wood

STUDIES ON PARTICLE (IPST)

Low headspace drying under steam

We had previously observed that heating OSB flakes wrapped in aluminum foil (to simulate a low headspace) preferentially released VOCs without giving up much moisture. We hypothesized that the low headspace inside the foil prevented water loss but allowed removal of VOCs which are present in much smaller quantities. These measurements were made on a small scale (3 g.), and we scaled up the work using 800 g. of sawdust (obtained from Weyerhaeuser's Adel GA mill) and our 1.5 cu ft. oven. The samples were processed in two stages. First, the material was heated without any gas flow through the oven in order to allow saturation of the headspace in the oven. The sample was cooled for 30 minutes and then reheated at 130°C under a 10 lpm airflow for 2 hours, with a sidestream taken for Method 25A VOC analysis. The results are listed in Table 6. The last entry in Table 6 represents a control where the low headspace heating stage was omitted, i.e. the furnish was continuously dried under a 10 lpm air stream. The VOC and water loss are similar for both the two stage samples and the control, indicating no preferential VOC loss in the first stage. However, appreciable water loss occurred in the two-stage samples, and it appears that a smaller headspace to further restrict water loss is required for VOC pre-extraction to be effective.

Unit for low-headspace VOC extraction with steam

An apparatus to pre-extract VOCs from wood with steam was constructed. The device, illustrated in Figure 13, uses saturated steam to suppress drying of the wood while allowing volatiles to be extracted in concentrated form. The vessel is a 4" OD x 27" long stainless steel cylinder with a quick disconnect union located 6 inches from one end for sample loading and unloading. The cylinder can accept up to 100 g of furnish, and rests on a frame fitted with ball bearing pillow blocks. The vessel is configured for batch drying, but can easily be refitted to recirculate a single charge of steam if vapor movement inside the vessel becomes necessary. Steam of 15-50 psia can be fed into the vessel.

The vessel components are (i) a steam vortex meter with pressure and temperature outputs to enable calculation of the mass flow rate of the steam into the vessel, so that the VOC concentration can be accurately determined; (ii) needle valves that can be shut during steaming to retain the steam in the vessel after injection; and (iii) heating tape wrapped around the vessel to maintain temperatures of up to 500^{0}C to minimize steam condensation inside the cylinder. A motor can be added, if necessary, to rock the cylinder back and forth.

Table 6: VOCs from low-headspace sawdust drying

run	stage 1[1]		stage 2[2]		
	conditions	wt. loss	conditions	addnl. wt. loss[3]	VOC (μg/g)[4]
79-2	130^{0}C, 60 min.	10.75%	130^{0}C, 120 min.	21.75	128
79-4	200^{0}C, 15 min.	6.12%		22.13	142
79-3	control			22.38	142

Dried under [1]no air flow, and under [2]10 lpm. [3]Based on the initial weight. [4]Green basis

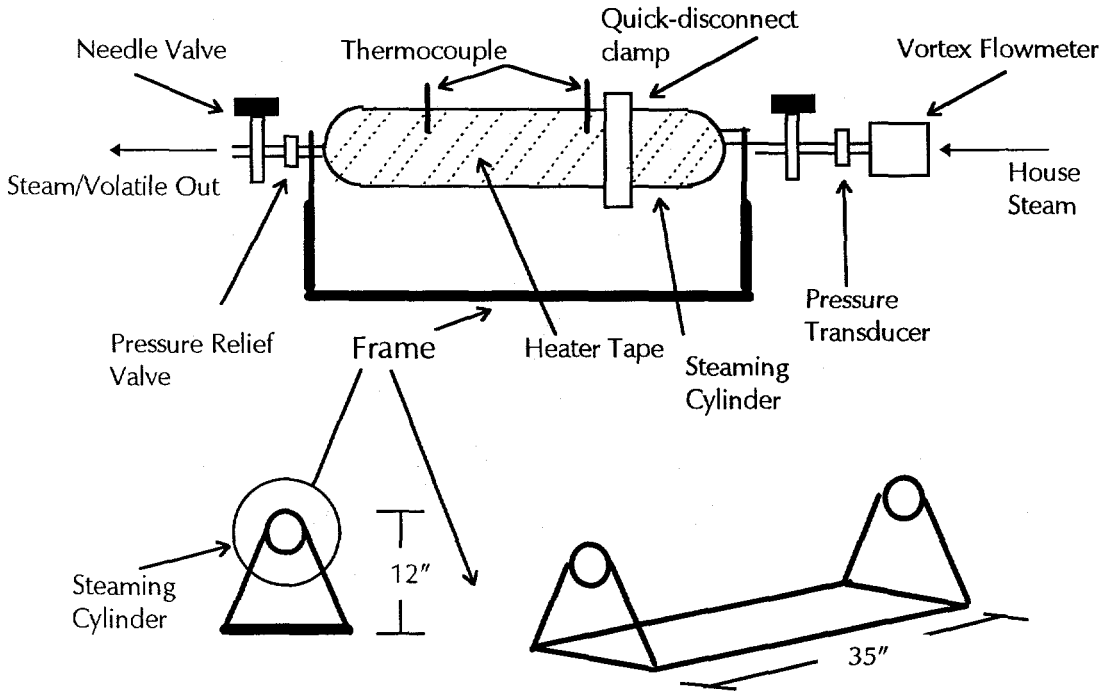

Figure 13: Schematic of a low-headspace steaming unit

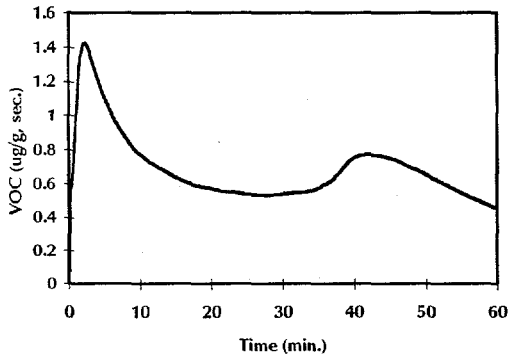

Figure 14: VOCs from run 153-3 (control)

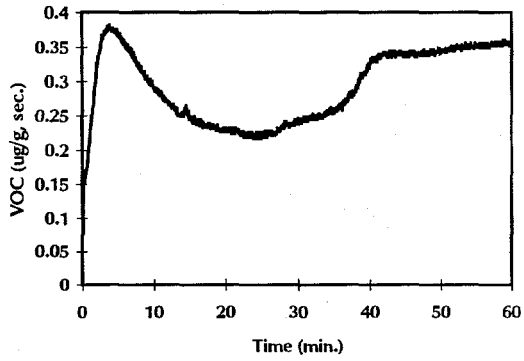

Figure 15: VOCs from run 153-5 (steamed at 179°C)

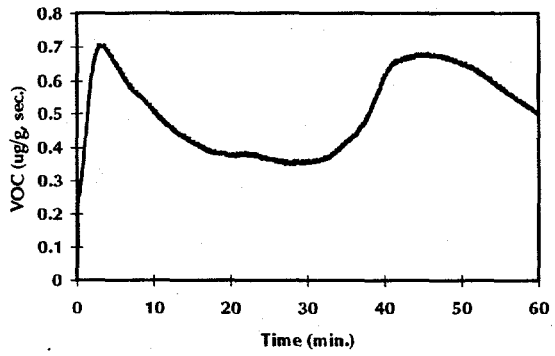

Figure 16: VOCs from run 160-3 (steamed at 119°C)

Particle was first steamed in the Figure 13 apparatus, and the steam was then vented through a methanol trap. The steamed wood was dried in the tube furnace at 130°C for 60 minutes. The furnace consists of a heated ceramic tube in which 3-5 g. of furnish is placed in a boat. One end of the tube is open; the other is connected to a Method 25A detector, whose sampling pump draws air through the tube. Thus, all the emissions from the sample enter the detector. VOCs integrated over both 30 and 60 minutes are shown in Table 7; the furnish is effectively dry in 30 minutes. Over 50% of the VOC was removed (the difference between control and sample runs) during steaming at high temperature (>150°C). The final column in Table 7 refers to the VOCs recovered in the trap as a percentage of that lost from the wood. Decreasing steam treatment from 30 to 15 minutes decreased VOC removal by about 10%. On the other hand, increasing steaming time from 30 to 60 minutes did not increase the VOCs extracted to any substantial extent, but the furnish turned noticeably darker. Much less VOC was lost during steaming at lower temperature as shown in Table 8. The recovery is low, probably because losses on vessel surfaces are proportionately higher. Typical VOC profiles are illustrated in Figures 14-16. Note that the intensity of the signals drops with increasing steaming temperature.

The effect of re-steaming once-steamed wood was determined by first steaming at 179°C for 30 minutes, allowing the sample to cool, and then steaming it again for another 30 minutes at 173°C. This wood was now dried in the tube furnace, and the VOCs measured are listed in Table 9. Although considerable additional VOC was lost, the wood particles darkened after the second steam treatment.

Steam extraction of VOC from particle at atmospheric pressure

The previous experiments were conducted under pressure since the steam was introduced under atmospheric pressure, and the sealed unit was then heated. In order to separate the effects of temperature and pressure, particle was first steamed at about 167°C for 10 minutes under sealed conditions (with the valve closed), and then for 20 minutes with the needle valve slightly open. Vapor released during steaming was led to a methanol trap. The steamed wood was then heated in the tube furnace and the VOCs measured. The trap methanol was analyzed for pinene. The results of these experiments are designated in Table 10 as the series 177 measurements.

Table 7: VOC emissions from particle at 130°C after high temperature steaming						
run	steam time (min)	steam temp (°C)	pressure (psi)	VOC (µg/g, dry basis), 60 min	VOC (µg/g, dry basis), 30 min	VOC recovered (%)
particle from Weyerhaeuser, Adel (11.18.96)						
153-1	control	NA		2350	1300	
153-2	control	NA		2460	1350	
153-3	control	NA		2460	1330	
153-4	control	NA		2580	1320	
155-5	control	NA		2650	1330	
155-6	control	NA		2720	1380	
160-1	control	NA		2400	1000	
160-2	control	NA		2270	1000	
avg.				**2500 ± 100**	**1300 ± 200**	
153-5	30	179	142	1050	475	112
153-6	30	179		1180	488	
153-7	30	179		1410	504	
153-8	30	179		1100	472	
avg.				**1200 ± 100**	**490 ± 10**	
155-1	30	174	126	1180	502	89
155-2	30	174		1230	518	
155-3	30	174		1310	580	
155-4	30	174		1050	455	
avg.				**1190 ± 90**	**510 ± 40**	
157-1	15	174	142	1500	620	81
157-2	15	174		1490	598	
157-3	15	174		1330	533	
157-4	15	174		1430	586	
avg.				**1440 ± 70**	**580 ± 30**	
168-4	60	172	121	740	430	76
168-5	60	172		1360	634	
168-6	60	172		803	433	
168-7	60	172		874	471	
avg.				**1000 ± 300**	**490 ± 80**	
170-1	60	178		879	464	
170-2	60	178		1020	556	
170-3	60	178		858	463	
170-4	60	178		931	548	
avg.				**920 ± 60**	**510 ± 40**	
173-1	30	178	69	1710	700	32
173-2	30	178		1620	722	
173-3	30	178		1570	656	
173-4	30	178		1560	673	
avg.				**1610 ± 60**	**690 ± 30**	
174-1	30	152		1760	813	
174-2	30	152		1820	739	
174-3	30	152		1540	612	
avg.				**1700 ± 100**	**720 ± 80**	

Table 8: VOC emissions from particle at 130°C after low temperature steaming						
run	steam time (min)	steam temp (°C)	pressure (psi)	VOC (µg/g, dry basis), 60 min	VOC (µg/g, dry basis), 30 min	VOC recovered (%)
particle from Weyerhaeuser, Adel (11.18.96)						
160-3	30	119	28	1820	815	18
160-4	30	119		1850	847	
160-5	30	119		2010	824	
160-6	30	119		2010	821	
avg.				**1920 ± 90**	**830 ± 10**	
161-1	30	122	30	1970	878	12
161-2	30	122		1690	762	
161-3	30	122		1860	848	
161-4	30	122		1704	752	
avg.				**1800 ± 100**	**810 ± 50**	

Table 9: VOC emissions from particle at 130°C after two steam treatments						
run	steam time (min)	steam temp (°C)	pressure (psi)	VOC (µg/g, dry basis), 60 min	VOC (µg/g, dry basis), 30 min	VOC recovered (%)
particle from Weyerhaeuser, Adel (11.18.96)						
control (Table 7) avg.				**2500 ± 100**	**1300 ± 200**	
156-1	30	173	125	351	292	14
156-2	30	173		350	306	
156-3	30	173		350	291	
156-4	30	173		395	300	
avg.				**360 ± 20**	**297 ± 6**	

Table 10: VOC emissions from particle at 130°C at reduced pressure					
run	steam time (min)	steam temp (°C)	VOC (µg/g, dry basis), 60 min	VOC (µg/g, dry basis), 30 min	VOC recovered (%)
particle from Weyerhaeuser, Adel (11.18.96)					
control (Table 7) avg.			**2500 ± 100**	**1300 ± 200**	
177-1[1]	30	167	903	346	25
177-2[1]	30	167	899	351	
177-3[1]	30	167	875	348	
177-4[1]	30	167	907	346	
avg.			**900 ± 10**	**348 ± 2**	
178-1	30	168	1220	457	40
178-2	30	168	937	411	
178-3	30	168	1180	471	
178-4	30	168	923	366	
avg.			**1100 ± 100**	**430 ± 40**	
[1]sealed for the first 10 minutes					

Substantial VOC removal occurred during steaming. A possible mechanism for the low VOC recovery is condensation in the uninsulated, unheated viton tube stretching from the needle valve to the methanol trap. Runs were also made where the needle valve was partially opened immediately after steam-charging was complete, i.e. the material was steamed continuously at atmospheric pressure. The results, designated as the 178 series in Table 13 show VOC removal of about 60%. These results demonstrate that high temperature, and not high pressure, is key to VOC extraction, and that steaming particle at elevated temperature is a viable means of extracting VOCs.

RF-pretreatment of particle

Sawdust (400 g.) obtained from the Weyerhaeuser Adel mill was heat-sealed in a 13 sq in. plastic bag and irradiated with an applied power of 0.6 A. Two electrode gap positions were used. No weight loss occurred during irradiation, and a 25% reduction in VOC was realized in the best case as shown in Table 11. The irradiation period was too brief since the material was cool to the touch. At 31 g./sq. in., the furnish density was fifteen-fold higher than that used for OSB. The VOC profiles of the irradiated furnishes during the subsequent thermal drying were very similar to those of the controls. Either steam or RF is capable of removing VOC from the furnish with minimal loss of water. At this stage we have established the gross feasibility of either technique in the laboratory. These will be refined in the second year of the study.

STUDIES ON OSB AND VENEER (IPST)

Low headspace drying under steam

OSB was first steamed in the Figure 13 apparatus, and then heated in the tube furnace at 130°C, and the VOCs measured. Ambient pressure steam was injected into the vessel for 3 minutes, and the vessel was sealed by closing the needle valve. The temperature was brought up to the desired set point which was controlled by adjusting the current to the heating tapes. After steam treatment, the vapor inside the vessel was released into 100 mL of methanol for VOC analysis by gc, and the vessel flushed with fresh steam for 30 seconds.

Table 11: VOC emissions from sawdust at 130°C (plastic wrapped)

run no.	RF time (sec.)	electrode gap (inches)	total weight loss (%)	VOC (µg/g) 60 min. (avg.)
130-1	0		49.54	3960
130-2	0		49.37	3990
130-3	0		49.37	3980 **(3980)**
130-4	30	7	48.02	3990
133-5	30	7	48.96	3970 **(3980)**
130-6	60	7	48.61	3540
130-7	60	7	48.06	3690 **(3610)**
130-8	120	7	47.67	3430
130-9	120	7	47.18	3400 **(3410)**
130-10	60	10.25	49.09	3690
130-11	60	10.25	50.16	3660 **(3670)**
130-12	180	10.25	46.39	2960
130-13	180	10.25	47.31	3030 **(3000)**

Two to four runs were made from each batch of steamed flakes. Results from flakes steamed at high temperature (>170°C) are presented in Table 12. The difference between the control (no steam) and sample runs represents the VOC extracted by steam. Over 50% VOC was removed after 30 minutes of steaming. Data are presented for both 30 and 60 minute treatments. As before, the wood was dry at 30 minutes or less, and the 60-minute reflects an over-dried situation. The last column is the pinene recovered in the methanol trap (as measured by gc) as a percentage of total VOC (pinene and other components) lost from the wood. Despite the high variability, it is clear that a substantial fraction of the VOCs released can be recovered. One anomaly was noted: no VOC was lost from samples 151-5 through 151-8 in Table 12, and we are unable to explain this outcome. About 10-25% by weight of moisture was gained by the wood, but this is probably an artifact in that the moisture was deposited on the wood surface, as opposed to being absorbed by the furnish. The pressure within the cylinder was determined from steam tables using the temperature measured within the cylinder. Steaming at low temperature (116°C) removes much less VOC, if any, as shown in Table 13. Clearly, the steam must be at high temperature in order to effect VOC removal. We are presently working on a simple VOC collection system, after which we will explore commercial feasibility.

VOC profiles from steamed and control furnishes are compared in Figures 17 and 18. Signal intensities are much weaker for the latter, since VOC was removed during steaming. The delay in the second signal could well be an artifact, since the furnish picked up water during steaming, and the delay may reflect evaporation of this material.

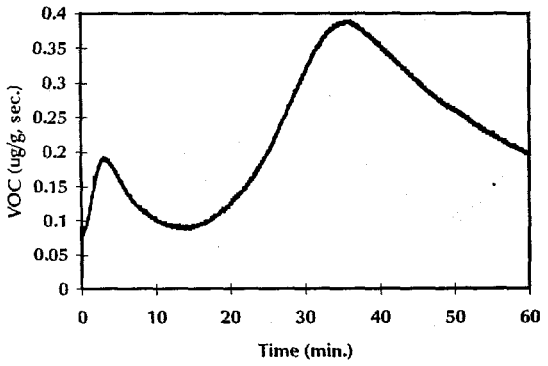

Figure 17: VOCs from run 140-1 (control)

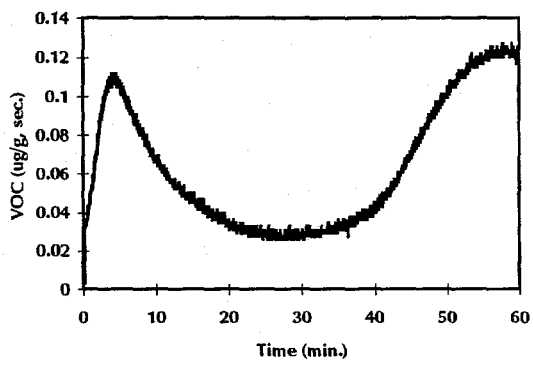

Figure 18: VOCs from run 140-3 (steamed at 171°C)

Table 12: VOC emissions from OSB after high temperature steaming						
run	steam time (min)	steam temp (°C)	pressure (psi)	VOC (µg/g, dry basis), 60 min	VOC (µg/g, dry basis), 30 min	VOC recovered (%)
OSB from G-P Grenada (11.13.96)						
140-1	control			805	267	
140-2	control			788	265	
140-3	30	171	118	227	95	
140-4	30		118	437	149	
OSB from G-P Grenada (11.21.96)						
150-1	control	NA		909	307	
150-2	control	NA		681	290	
150-3	control	NA		788	291	
150-4	control	NA		732	205	
avg.				**780 ± 80**	**270 ± 40**	
150-6	30	184	161	367	133	151
150-7	30	184		386	135	
150-8	30	184		436	143	
150-9	30	184		336	129	
avg.				**380 ± 40**	**135 ± 5**	
OSB from G-P Dudley (2.3.97)						
151-1	control	NA		418	245	
151-2	control	NA		375	175	
151-3	control	NA		490	263	
151-4	control	NA		667	349	
avg.				**500 ± 100**	**260 ± 60**	
151-5	30	181	151	556	338	123
151-6	30	181		340	216	
151-7	30	181		534	291	
151-8	30	181		467	244	
avg.				**470 ± 80**	**270 ± 50**	
152-1	30	172	121	315	161	47
152-2	30	172		191	116	
152-3	30	172		241	121	
152-4	30	172		144	87	
avg.				**220 ± 60**	**120 ± 30**	

Table 13: VOC emissions from OSB[1] at 130°C after low temperature steaming					
run	steam time (min)	steam temp (°C)	pressure (psi)	VOC (μg/g, dry basis), 60 min	VOC (μg/g, dry basis), 30 min
OSB from G-P Dudley (1.14.97)					
142-1	0 (control)			1078	490
142-2	0 (control)			1046	444
142-3	0 (control)			744	272
142-4	0 (control)			731	275
142-5	0 (control)			875	303
142-6	0 (control)			881	288
avg.				**900 ± 100**	**350 ± 90**
143-1	30	116	25	701	341
143-2	30			606	261
143-3	30			639	328
143-4	30			597	285
143-5	30			780	273
avg.				**670 ± 70**	**300 ± 30**
OSB from G-P Grenada (8.5.96)					
149-1	control	NA		1033	251
149-2	control	NA		1010	124
149-3	control	NA		263	45
149-4	control	NA		511	116
avg.				**700 ± 300**	**130 ± 70**
149-5	30	116	25	740	414
149-6	30	116		674	151
149-7	30	116		867	172
149-8	30	116		590	215
avg.				**700 ± 100**	**200 ± 100**

RF-pretreatment of OSB

Irradiation at 1 amp

OSB (100 g.) from G-P, Grenada, MS, was wrapped in a plastic bag and irradiated with a 7" electrode gap setting with an applied current of 1A. The area of the bag was 48 sq in. which translates to a furnish density of 2.1 g/square inch. A companion sample was irradiated open, i.e. without any plastic covering. The flakes were then processed in the tube furnace with the emissions being monitored by Method 25A. The desired condition of low water loss was not reached since too much power was applied. It is not possible to determine power absorption *a priori*, and the dryer parameters must be set through trial and error. The covered and uncovered RF-treated flakes showed very similar VOC profiles since the steam generated inadvertently ruptured the plastic covering.

The profile of an irradiated sample is compared to that of a control (no RF) in Figures 19 and 20. Note that the initial peak in the control is reduced upon irradiation, and that the second

peak emerges earlier. Also, much less VOC is lost per unit of water during RF drying. For example, 1,970 μg/g was lost from the control, whereas only 819 μg/g was released from the irradiated flakes (119-1,2,3) dried to roughly the same moisture content. Lower levels of irradiation led to intermediate profiles.

Irradiation at 0.6A

In order to minimize water loss during irradiation, the RF intensity was reduced by decreasing the applied current to 0.6A. OSB received from G-P Dudley on 10.17.96 was wrapped in plastic and irradiated under two different electrode gap settings. The wider gap is associated with lower power. The irradiated material was then oven-dried as before. The results shown in Table 14 demonstrates that little water is lost during irradiation. Low-power extended drying (as in runs 129-16,17) seems to be the most effective; roughly 40% VOC is released during irradiation with only 3% water loss. No major differences were noted between the VOC profiles of the irradiated materials and those of the controls. The RF settings will be optimized during the second year of the project.

RF-pretreatment of veneer

Green veneer collected from G-P, Monticello, GA was cut into 5" x 5" squares wrapped in plastic, and irradiated with RF. The electrode gap setting was 7" and the applied power was at 1A. The area of the bag was 35" which translates to a furnish density of 2 g/square inch. The furnish was then coarsely broken up and processed in the tube furnace with the emissions being monitored by Method 25A. The results are listed in Table 15, and two representative profiles are illustrated in Figures 19 and 20. Too much power was applied since an appreciable amount of water was lost during irradiation. Even so, consider runs 122-7,8,9 in Table 15. Approximately 40% of the removable water is lost by RF, but a comparison with the control shows that about 60% of the VOC is released during irradiation. Hence, much more VOC per unit of water is lost than is the case for OSB. The probable reason is furnish thickness as will be discussed later. A comparison of Figures 19 and 20 shows that RF redistributes the VOCs in wood.

Table 14: VOC emissions from OSB at 130°C (plastic wrapped)

run no.	RF time (sec.)	electrode gap (inches)	weight loss during RF (%)	total weight loss (%)	VOC (μg/g) 60 min. (avg.)
129-1	0			51.36	442
129-2	0			55.46	399
129-3	0			51.94	469 **(437)**
129-4	30	7	0	50.09	359
129-5	30	7	0	50.08	352 **(356)**
129-7	60	7	1.0	50.72	335
129-8	60	7	1.0	51.68	283 **(309)**
129-10	120	7	8.7	53.70	306
129-11	120	7	8.7	55.65	261
129-12	120	7	8.7	54.55	249 **(272)**
129-13	60	10.25	1.1	49.14	390
129-14	60	10.25	1.1	49.64	373 **(381)**
129-16	120	10.25	3.4	54.97	261
129-17	120	10.25	3.4	56.40	276 **(269)**

Table 15: VOC emissions from veneer at 130°C (plastic wrapped)				
run no.	RF time (sec.)	weight loss during RF (%)	total weight loss (%)	VOC (µg/g) 60 min. (avg.)
123-10	no		57.03	1235
123-11	no		56.25	1269
123-12	no		58.52	1290 (**1265**)
122-4	45	31.51	61.49	500
122-5	45	31.51	58.93	481
122-6	45	31.51	61.01	395 (**459**)
122-7	60	24.86	66.76	468
122-8	60	24.86	66.74	632
122-9	60	24.86	67.80	530 (**543**)
122-10	90	47.19	54.98	254
122-11	90	47.19	54.30	254
122-12	90	47.19	55.19	209 (**239**)
122-13	120	46.64	57.15	239
122-14	120	46.64	56.89	246
122-15	120	46.64	54.87	295 (**260**)
122-16	180	28.64	42.38	211
122-17	180	28.64	42.28	172
122-18	180	28.64	42.77	154 (**179**)

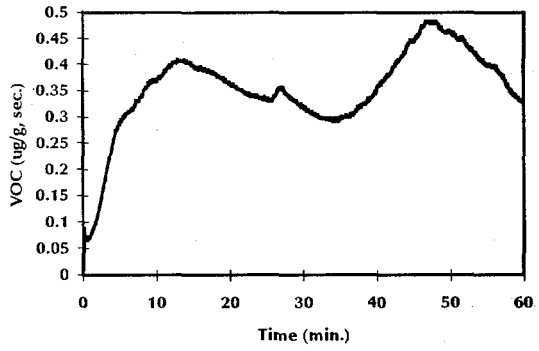

Figure 19: VOC profile of thermally dried veneer (123-11)

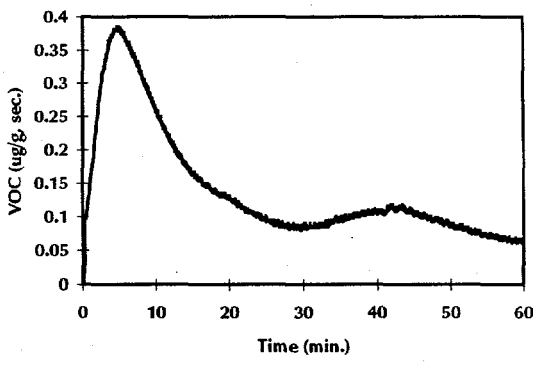

Figure 21: VOC profile of RF-treated veneer (122-4)

COLLECTION OF VOCs (IPST)

Since low headspace steaming of particle and OSB releases substantial quantities of VOC, attempts were made to collect this material, which is turpentine, and is of appreciable commercial value. Two approaches were pursued; adsorption of the organics on a plug of porous, hydrophobic polyethylene disks, and stripping with silicone oil. Particle (400 g.) from the Weyerhaeuser Adel facility was steamed for 30 minutes at approximately 177°C in the apparatus of Figure 13.

The steam was fed through a 7.6 cm long Teflon pipe nipple containing 2.54 cm diameter 40 or 10 μm polyethylene disks. The flow through the disks was then trapped in methanol.

The steamed wood was then dried at 130°C for 60 minutes in our tube furnace, and the VOCs released measured by Method 25A are recorded in Table 16. The trap methanol was analyzed by gc, and the VOCs from the disks were eluted by methanol and also analyzed by gc. The results show that approximately 50% of the VOC in the furnish is removed by steam. However, the VOC deposited on the disks is small. Possibly, the elevated temperature of the steam inhibits sorption.

Next, a series of experiments were conducted to determine whether silicone oil would serve as a better trap than methanol. Again, a 400 g sample of particle was placed into the extraction unit, and steamed for 30 minutes at approximately 177°C. A 100 mL silicone oil trap was placed at the outlet of the steaming vessel, followed by a second trap containing 100 mL of methanol, to capture any VOCs not retained in the silicone oil. The silicone oil trap was maintained at 100°C in a water bath to prevent water condensation in the trap. Since the oil could not be analyzed directly, a parallel experiment was run with only the methanol trap, so that the material retained by the oil could be obtained by difference. Seven lots of wood were dried with the *same* silicone oil to determine the holding capacity of the oil. The methanol, however, was changed after each run. The steamed particle was then heated in our tube furnace as before, and the emissions monitored by Method 25A are listed in Table 17. The oil retained over 98% of the VOCs in the first experiment. A minimum of 76% VOC was retained in experiments 2 through 5. Experiments 6 and 7 retained only 62% and 69%, respectively, indicating that the holding capacity of the oil for VOC was beginning to diminish. Thus, the oil is able to retain a substantial amount of VOCs *without* condensing the steam. Thus, the zero discharge permit of a commercial facility would not be compromised.

Table 16: VOC emissions from particle at 130°C					
sample no.	VOC (μg/g[1]) 60 min. (avg.)	VOC (μg/g[1]) 30 min. (avg.)	steam temp. (°C)	VOC (μg/g[1]) trap	disks
control-Weyerhauser Adel particle					
185-1	1120	564			
185-2	1152	523			
185-3	1107	506			
185-4	1157	528			
187-5	1132	527			
187-6	1268	593			
190-5	1232	514			
190-6	968	457			
7-5	909	414			
7-6	947	432			
average	**1100 ± 100**	**510 ± 50**			
trapping on 40 μm porous polyethylene, half cartridge					
185-5	499	161			
185-6	584	199			
185-7	553	176			
185-8	478	170	171	129	2
average	**530 ± 40**	**180 ± 10**			
trapping on 40 μm porous polyethylene, full cartridge					
187-1	540	234			
187-2	514	234			
187-3	495	233			
187-4	524	246	181	64	17
average	**520 ± 20**	**237 ± 5**			
10 μm porous polyethylene, half cartridge					
188-1	394	170			
188-2	406	191			
188-3	413	178			
188-4	401	188	177	254	9
average	**404 ± 7**	**182 ± 8**			
[1]of green wood					

Table 17: VOC emissions from particle at 130°C				
sample no.	VOC ($\mu g/g^1$) 60 min. (avg.)	VOC ($\mu g/g^1$) 30 min. (avg.)	steam temp. (°C)	VOC ($\mu g/g^1$) in methanol
control #1				
190-1	484	226		
190-2	475	224		
190-3	417	213		
190-4	452	221	181	116
average	**460 ± 30**	**244 ± 5**		
control #2				
13-1	473	244		
13-2	498	270		
13-3	526	247		
13-4	541	250	177	100
average	**510 ± 30**	**250 ± 10**		
control #3				
14-1	523	281		
14-2	435	248		
14-3	494	260		
14-4	454	251	182	106
average	**480 ± 30**	**260 ± 10**		
silicone oil experiment #1				
189-1	678	304		
189-2	588	279		
189-3	560	269		
189-4	572	260	184	2
average	**600 ± 50**	**280 ± 20**		
silicone oil experiment #2				
4-1	591	304		
4-2	626	335		
4-3	584	319		
4-4	554	303	183	23
average	**590 ± 30**	**310 ± 10**		
silicone oil experiment #3				
5-1	401	200		
5-2	482	230		
5-3	494	240		
5-4	460	224	179	9
average	**460 ± 40**	**220 ± 10**		
silicone oil experiment #4				
7-1	472	250		
7-2	505	282		
7-3	457	252		
7-4	502	268	191	21
average	**480 ± 20**	**260 ± 10**		

Table 17 (cont.): VOC emissions from particle at 130°C				
sample No.	VOC ($\mu g/g^1$) 60 min. (avg.)	VOC ($\mu g/g^1$) 30 min. (avg.)	steam temp. (°C)	VOC ($\mu g/g^1$) in methanol
silicone oil experiment #5				
8-1	586	317		
8-2	605	334		
8-3	552	304		
8-4	501	288	188	26
average	**560 ± 40**	**310 ± 20**		
silicone oil experiment #6				
10-1	484	230		
10-2	403	214		
10-3	383	209		
10-4	409	209	192	41
average	**420 ± 40**	**216 ± 9**		
silicone oil experiment #7				
12-1	575	296		
12-2	564	298		
12-3	509	277		
12-4	526	293	179	33
average	**540 ± 30**	**291 ± 8**		
[1]of green wood				

Recovery of VOCs from silicone oil

In order to determine the ease with which the VOCs could be removed from the silicone oil, the oil from the preceding experiment was placed in a 100°C water bath and air-stripped (0.4 lpm) into a methanol trap. The methanol in the trap was changed periodically, and the VOCs in each charge were analyzed by gc. The estimated VOC level in the silicone oil was 300 mg, and as shown in Table 18, 92% removal was achieved by 72 liters of air. The air volume is not optimized, since nozzles which generate smaller bubbles will be more efficient. However, it is clear that VOCs can be efficiently removed from oil with an air stream.

Table 18: VOC stripping from silicone oil			
methanol charge (no.)	**incremental collection time (min)**	**total time (min)**	**VOC (mg) in methanol**
1	15	15	48.9
2	15	30	42.1
3	15	45	63.1
4	30	75	49.5
5	45	120	46.5
6	60	180	26.0
total VOC recovered from silicone oil			**276**

Collection of VOCs from low-headspace RF treatment of lumber

Preliminary measurements were made to determine the efficiency of VOC collection from the headspace during RF treatment. The trap in Figure 7 was filled with 250 mL of methanol in an ice bath. Pine lumber (2.679 kg, 1.75 in. x 3.25 in x 44 in.) was irradiated at 1.1 amps with cycling to keep the external temperature at about 100°C. The internal temperature could not be monitored, since the thermocouple was blown out through steam pressure. The wood was removed after irradiation, the condensed steam inside the vessel was collected, and the vessel was then rinsed with 250 mL of methanol. The material trapped in methanol was released during irradiation, and is referred to henceforth as *trapped emissions*. VOCs in this fraction are reported in Table 19. The condensate and rinsate are collectively called *condensate/rinsate*. The trapped emissions were clear, except for an oily layer at the surface. The milky condensate/rinsate was clarified through addition of 2.115 g. of a 1:1 methanol:ether solution to 1.7849 g. of the condensate/rinsate. The resin acid distribution is provided in Table 20. Most of the terpenes are carried out of the RF-unit with a small amount of water. At 0.05%, the amounts are appreciable, corresponding to about 1 lb/ton. This value is by no means optimized, but it is roughly comparable to the difference between control and RF-treated values in Table 2. Hence, much of the VOCs removed from wood by RF is recoverable.

TRANSPORT OF VOCs IN WOOD (MSU)

Effect of lumber size on VOC release

Lumber, 2"x12"x23" (6 pieces), and 2"x6"x23" (12 pieces) were dried in duplicate at 245°F for 16 hours under an airflow corresponding to 1 lpm per kg. of green wood. The results are provided in Table 22, and the profiles illustrated in Figure 23. The larger pieces contained a greater proportion of heartwood since they were cut from the centers of large mature trees. The smaller pieces were milled from smaller immature trees or from the outer sapwood portion. Hence, the any dimensional effect was masked by the heartwood/softwood differences.

Table 19: Analysis of trapped emissions and condensate/rinsate

	α-pinene ($\mu g/g^1$)	β-pinene ($\mu g/g^1$)	total VOCs ($\mu g/g^1$)	total resin acids ($\mu g/g^1$)
trapped emissions	250	187	518	0
condensate/rinsate	0.45	0.46	6.4	520*

[1] of green wood

Table 20: Composition of resin acids in the condensate/rinsate

	retention time (min)	percent
pimaric acid	23.755	5
unknown	24.035	17
isopimaric acid	24.282	28
dehydroabietic acid	24.637	9
abietic acid	25.096	27
neoabietic acid	25.742	14

Table 21: Effect of size on VOC emissions				
ID	charge	MC% (initial)	MC% (final)	VOC (lbs/ton dry wood)
A	2x12x23 (6 pieces)	101.7	7	5.77
B	2x6x23 (12 pieces)	108.7	0	2.77
C	2x6x23 (12 pieces)	93.5	0	2.21
D	2x12x23 (6 pieces)	73.9	7	6.73

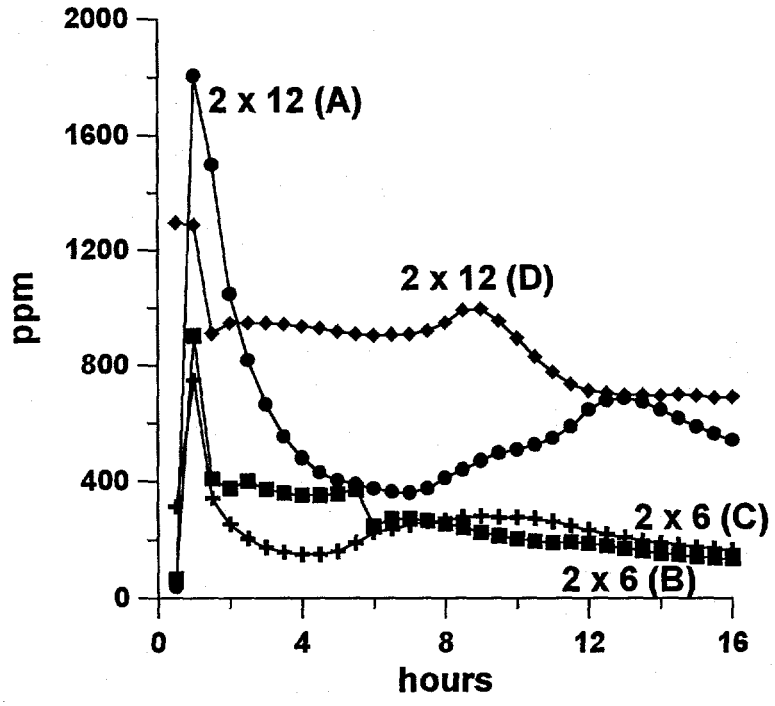

Figure 21: Effect of sample size on VOC emissions

Diffusion of water in wood

The relative drying rates of the transverse, tangential, and radial faces of wood were determined since work in our parallel EPRI project indicates that VOC release is related to the loss of water in wood. The tangential plane faces the outer portion of the wood (Figure 22). The radial face creates a plane reaching from the outer portion of the tree towards the inner core. The transverse, or cross section, is the face exhibiting growth rings. The sample cubes for the water diffusion in wood experiments were cut so all three faces were present in equal dimensions of 20 mm per side with faces appearing on the opposite sides of the cube. Five cubes and two moisture sections were taken from each of 3 boards, yielding a total of 15 sample cubes. An epoxy coating material was then applied to the cubes in the five groups to limit the transport of water through the epoxied face as shown in Table 22.

Table 22: Drying rates as a function of surface orientation					
treatment no.	transverse	radial	tangential	MC change, % / min (r^2)	proportional drying ratio
1	coated	coated	coated	0.588 (0.95)	0.31
2	open	coated	coated	1.459 (0.88)	0.78
3	coated	open	coated	0.715 (0.90)	0.38
4	coated	coated	open	0.929 (0.88)	0.49
5	open	open	open	1.881 (0.86)	1.00

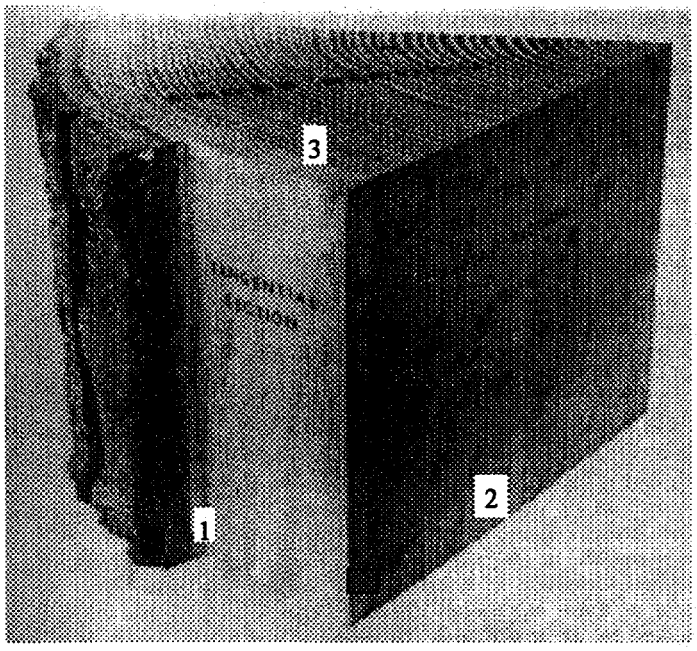

Figure 22: Cross-section of tree naming the three planes; (1) tangential, (2) radial, and (3) transverse (cross section)

Treatment 1 was the control for the coating which indicated the resistance to water loss provided by the coating. The coating was applied to two faces of each cube for treatments 2-4; hence, water could only be lost through the open face. Finally, treatment 5 was left open. The coated cubes were reweighed and recorded as the adjusted green weight. The cubes were placed in a 120°C oven and weighed every 20 minutes until each cube reached its calculated weight at the fiber saturation point, or approximately 30% moisture content. Moisture contents were calculated for each interval, and linear regressions performed to determine drying rates for each treatment group. The results indicate that epoxy reduces the flow by a factor of 3.24; therefore the surfaces coated with epoxy emit vapor at 31% of normal flow.

Clearly, the high-temperature drying rates are different for the three primary wood faces, with the transverse surface experiencing the greatest change in moisture content. At the start of a kiln cycle, there is a large drop in wood MC as the water near the ends moves out via capillary

action. This phenomenon was demonstrated with the epoxy and cubes; the cubes with the transverse surface exposed dried quickly. At the start of a kiln cycle there is also a peak in the amount of VOC emissions observed from the wood.

Seasonal variation of monoterpenes and resin acids in Loblolly Pine

Samples were collected from twelve loblolly pines located in Moorehead Bottom on the MSU forest on a monthly basis from February to June, 1997. A twelve inch increment borer with a core diameter of 0.200 inches was used to collect cores at a height of approximately 42 inches. Each core was divided into three sections approximately four inches in length and labeled as outside, middle and inside sections. Each sample was extracted with methylene chloride and the sample extract was analyzed for monoterpenes and resin acids by gas chromatography with flame ionization detection. Target compounds were a-pinene camphene, b-pinene, limonene, fenchyl alcohol, borneol, 4-allylanisole, methyl eugenol pimaric acid, isopimaric acid levopimaric acid, dehydroabietic acid, abietic acid and neoabietic acid. The amount of each compound was calculated on a dry sample weight basis. Sample analysis is complete for all sampling periods except June and are presented in Tables 23-26. Sample collection and analysis will continue on a monthly basis through January 1998. The results will be compiled into a data base to facilitate processing and statistical analysis.

Table 23: Percent extractives in February 1997 samples												
	1-inside	**1-middle**	**1-outside**	**2-inside**	**2-middle**	**2-outside**	**3-inside***	**3-middle***	**3-outside***	**4-inside***	**4-middle**	**4-outside***
A-Pinene	0.3238	0.0156	0.0117	0.1645	0.0148	0.0148	0.2220	0.0005	0.0000	0.0021	0.0117	0.0020
Camphene	0.0060	0.0002	0.0002	0.0000	0.0002	0.0002	0.0040	0.0000	0.0000	0.0000	0.0002	0.0000
B-Pinene	0.3082	0.0179	0.0135	0.0171	0.0009	0.0010	0.1175	0.0002	0.0000	0.0016	0.0055	0.0011
Myrcene	0.0272	0.0013	0.0012	0.0000	0.0005	0.0004	0.0048	0.0000	0.0000	0.0000	0.0006	0.0000
Limonene	0.0080	0.0002	0.0002	0.0000	0.0001	0.0001	0.0047	0.0000	0.0000	0.0002	0.0006	0.0000
Fenchyl Alcohol	0.0010	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000	0.0000	0.0000	0.0000	0.0000
Borneol	0.0037	0.0000	0.0002	0.0000	0.0000	0.0000	0.0104	0.0000	0.0000	0.0000	0.0000	0.0000
4-Allylanisole	0.0287	0.0009	0.0019	0.0000	0.0006	0.0006	0.0737	0.0000	0.0000	0.0000	0.0004	0.0007
Methyl Eugenol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pimaric Acid	0.0131	0.0019	0.0010	0.3444	0.0013	0.0008	0.1953	0.0005	0.0000	0.0035	0.0021	0.0011
Iso-Levo Pimaric Acid	0.1221	0.0072	0.0033	0.9241	0.0043	0.0022	1.8292	0.0009	0.0000	0.0144	0.0063	0.0036
Dehydroabietic Acid	0.0531	0.0078	0.0031	0.3657	0.0051	0.0026	1.1998	0.0065	0.0059	0.0310	0.0140	0.0054
Abietic Acid	0.2610	0.0319	0.0200	1.5762	0.0301	0.0212	3.8969	0.0026	0.0111	0.0525	0.0439	0.0254
Neoabietic Acid	0.0179	0.0015	0.0010	0.5035	0.0013	0.0008	0.2420	0.0001	0.0000	0.0013	0.0012	0.0008
	5-inside	**5-middle***	**5-outside***	**6-inside***	**6-middle***	**6-outside***	**7-inside**	**7-middle**	**7-outside***	**8-inside**	**8-middle**	**8-outside***
A-Pinene	0.3047	0.0016	0.0074	0.1274	0.0003	0.0001	0.0139	0.0181	0.0019	0.2438	0.0112	0.0002
Camphene	0.0056	0.0000	0.0001	0.0032	0.0001	0.0000	0.0000	0.0003	0.0000	0.0054	0.0002	0.0000
B-Pinene	0.0556	0.0005	0.0013	0.0827	0.0039	0.0000	0.0000	0.0035	0.0005	0.0995	0.0076	0.0002
Myrcene	0.0144	0.0001	0.0007	0.0026	0.0001	0.0000	0.0000	0.0006	0.0000	0.0020	0.0002	0.0000
Limonene	0.0051	0.0000	0.0001	0.0082	0.0002	0.0000	0.0000	0.0010	0.0002	0.0071	0.0001	0.0000
Fenchyl Alcohol	0.0015	0.0000	0.0000	0.0032	0.0001	0.0000	0.0000	0.0000	0.0000	0.0018	0.0000	0.0000
Borneol	0.0022	0.0000	0.0000	0.0040	0.0002	0.0000	0.0000	0.0000	0.0000	0.0032	0.0001	0.0000
4-Allylanisole	0.0168	0.0001	0.0003	0.0311	0.0013	0.0000	0.0150	0.0005	0.0002	0.0183	0.0003	0.0008
Methyl Eugenol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pimaric Acid	0.0062	0.0005	0.0008	0.0054	0.0024	0.0017	0.1712	0.0028	0.0013	0.0082	0.0014	0.0015
Iso-Levo Pimaric Acid	0.0571	0.0030	0.0030	0.0005	0.0091	0.0057	1.8946	0.0070	0.0027	0.0561	0.0037	0.0025
Dehydroabietic Acid	0.0315	0.0038	0.0035	0.0221	0.0058	0.0077	0.9998	0.0134	0.0055	0.0384	0.0066	0.0098
Abietic Acid	0.1124	0.0124	0.0218	0.1067	0.0221	0.0145	0.6336	0.0539	0.0260	0.2214	0.0292	0.0192
Neoabietic Acid	0.0089	0.0006	0.0009	0.0210	0.0030	0.0010	0.1053	0.0017	0.0007	0.0112	0.0009	0.0003
	9-inside	**9-middle**	**9-outside**	**10-inside**	**10-middle**	**10-outside**	**11-inside**	**11-middle**	**11-outside***	**12-inside**	**12-middle**	**12-outside**
A-Pinene	0.6549	0.0245	0.0262	0.1361	0.0281	0.0177	0.1464	0.0262	0.0058	0.1173	0.0234	0.0219
Camphene	0.0161	0.0005	0.0000	0.0022	0.0004	0.0003	0.0025	0.0004	0.0000	0.0000	0.0004	0.0003
B-Pinene	0.6025	0.0208	0.0266	0.0323	0.0085	0.0073	0.1144	0.0194	0.0042	0.0698	0.0136	0.0104
Myrcene	0.0103	0.0000	0.0000	0.0014	0.0005	0.0000	0.0020	0.0000	0.0000	0.0000	0.0004	0.0005
Limonene	0.0309	0.0013	0.0016	0.0198	0.0037	0.0020	0.0014	0.0003	0.0000	0.0015	0.0003	0.0005
Fenchyl Alcohol	0.0097	0.0000	0.0000	0.0009	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Borneol	0.0079	0.0000	0.0000	0.0011	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4-Allylanisole	0.0745	0.0039	0.0000	0.0092	0.0006	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0009
Methyl Eugenol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pimaric Acid	0.0198	0.0066	0.0014	0.0226	0.0011	0.0006	0.0094	0.0009	0.0000	0.0143	0.0007	0.0013
Iso-Levo Pimaric Acid	0.1520	0.0010	0.0051	0.0956	0.0055	0.0031	0.0413	0.0034	0.0000	0.0433	0.0020	0.0042
Dehydroabietic Acid	0.0631	0.0144	0.0023	0.1171	0.0058	0.0039	0.0444	0.0073	0.0000	0.0792	0.0031	0.0049
Abietic Acid	0.4001	0.0814	0.0192	0.2727	0.0126	0.0147	0.1476	0.0276	0.0000	0.2775	0.0135	0.0270
Neoabietic Acid	0.0561	0.0109	0.0023	0.0134	0.0004	0.0006	0.0079	0.0009	0.0000	0.0113	0.0005	0.0011
* Samples dried out during sonication.												

Table 24: Percent extractives in March 1997 samples												
	1-inside	**1-middle**	**1-outside**	**2-inside**	**2-middle**	**2-outside**	**3-inside**	**3-middle**	**3-outside**	**4-inside**	**4-middle**	**4-outside**
A-Pinene	0.6008	0.7436	0.0817	2.5597	0.1379	0.1186	2.3855	0.0730	0.0644	0.1607	0.3463	0.0831
Camphene	0.0127	0.0234	0.0010	0.0457	0.0018	0.0014	0.0624	0.0008	0.0007	0.0032	0.0057	0.0014
B-Pinene	0.2899	0.3983	0.0666	0.1874	0.0080	0.0061	0.9513	0.0140	0.0105	0.0282	0.1434	0.0368
Myrcene	0.0535	0.0605	0.0096	0.1038	0.0045	0.0049	0.1302	0.0022	0.0021	0.0049	0.0275	0.0057
Limonene	0.0346	0.0006	0.0026	0.0281	0.0011	0.0011	0.0744	0.0060	0.0007	0.0143	0.0222	0.0038
Fenchyl Alcohol	0.0072	0.0060	0.0000	0.0000	0.0000	0.0000	0.0092	0.0000	0.0000	0.0015	0.0000	0.0000
Borneol	0.0092	0.0003	0.0000	0.0000	0.0000	0.0000	0.0093	0.0000	0.0000	0.0029	0.0000	0.0000
4-Allylanisole	0.0611	0.0459	0.0205	0.0803	0.0077	0.0060	0.0780	0.0060	0.0098	0.0079	0.0163	0.0136
Methyl Eugenol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pimaric Acid	0.0259	0.3916	0.0136	0.0704	0.0166	0.0114	0.2148	0.0141	0.0137	0.5132	0.0246	0.0116
Iso-Levo Pimaric Acid	0.7090	0.3076	0.1491	0.7247	0.1799	0.1668	0.3417	0.0963	0.0971	0.1556	0.3060	0.0964
Dehydroabietic Acid	0.4026	0.2847	0.0230	0.2106	0.0318	0.0080	0.1615	0.0109	0.0059	0.1357	0.1199	0.0131
Abietic Acid	0.9582	0.7096	0.0451	0.2684	0.0524	0.0371	0.2915	0.0185	0.0187	0.1801	0.1002	0.0157
Neoabietic Acid	0.2639	0.1071	0.0247	0.1347	0.0330	0.0290	0.1025	0.0198	0.0204	0.0547	0.0404	0.0148
	5-inside	**5-middle**	**5-outside**	**6-inside**	**6-middle**	**6-outside**	**7-inside**	**7-middle**	**7-outside**	**8-inside**	**8-middle**	**8-outside**
A-Pinene	0.4873	0.0592	0.1220	0.3630	0.0818	0.0848	0.4652	0.0573	0.1145	0.2256	0.0801	0.0675
Camphene	0.0068	0.0006	0.0014	0.0120	0.0012	0.0012	0.0064	0.0004	0.0013	0.0030	0.0010	0.0008
B-Pinene	0.0585	0.0094	0.0125	0.1721	0.0846	0.0658	0.0582	0.0086	0.0176	0.0906	0.0404	0.0306
Myrcene	0.0225	0.0037	0.0074	0.0062	0.0024	0.0024	0.0146	0.0017	0.0043	0.0022	0.0012	0.0010
Limonene	0.0095	0.0005	0.0010	0.0389	0.0072	0.0046	0.0000	0.0030	0.0063	0.0058	0.0021	0.0016
Fenchyl Alcohol	0.0020	0.0000	0.0000	0.0094	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Borneol	0.0021	0.0000	0.0000	0.0110	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4-Allylanisole	0.0066	0.0009	0.0046	0.0092	0.0038	0.0073	0.0057	0.0013	0.0048	0.0060	0.0045	0.0068
Methyl Eugenol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pimaric Acid	0.3050	0.0042	0.0175	0.2250	0.0938	0.0835	0.1014	0.0084	0.0173	0.1735	0.0179	0.0149
Iso-Levo Pimaric Acid	0.4402	0.0875	0.1604	0.4061	0.0591	0.1688	0.4590	0.0772	0.1793	0.2203	0.1258	0.1134
Dehydroabietic Acid	0.2403	0.0287	0.0309	0.1963	0.0286	0.0214	0.2440	0.0167	0.0223	0.1495	0.0229	0.0134
Abietic Acid	0.3667	0.0257	0.0411	0.2791	0.0406	0.0271	0.2114	0.0111	0.0441	0.3013	0.0460	0.0375
Neoabietic Acid	0.1277	0.0124	0.0214	0.2252	0.0328	0.0755	0.0864	0.0126	0.0299	0.0518	0.0215	0.0186
	9-inside	**9-middle**	**9-outside**	**10-inside**	**10-middle**	**10-outside**	**11-inside**	**11-middle**	**11-outside**	**12-inside**	**12-middle**	**12-outside**
A-Pinene	4.6780	0.2348	0.1424	0.3916	0.0512	0.0863	0.0848	0.0395	0.0020	1.0750	1.6170	0.1398
Camphene	0.2468	0.0047	0.0021	0.0058	0.0005	0.0010	0.0000	0.0004	0.0000	0.0204	0.0486	0.0017
B-Pinene	1.5529	0.1447	0.0972	0.0509	0.0133	0.0228	0.0445	0.0205	0.0007	0.2999	0.3452	0.0463
Myrcene	0.0653	0.0044	0.0036	0.0051	0.0009	0.0016	0.0013	0.0009	0.0000	0.0219	0.0374	0.0035
Limonene	0.0333	0.0259	0.0131	0.0522	0.0073	0.0106	0.0018	0.0011	0.0000	0.0368	0.0995	0.0033
Fenchyl Alcohol	0.2011	0.0023	0.0000	0.0013	0.0000	0.0000	0.0000	0.0000	0.0000	0.0044	0.0191	0.0000
Borneol	0.2107	0.0024	0.0000	0.0017	0.0000	0.0000	0.0000	0.0000	0.0000	0.0068	0.0254	0.0000
4-Allylanisole	0.1419	0.0055	0.0030	0.0024	0.0009	0.0088	0.0000	0.0013	0.0000	0.0204	0.0223	0.0122
Methyl Eugenol	0.0000	0.0000	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.0000	0.0000
Pimaric Acid	3.3050	0.0693	0.0941	0.0850	0.0041	0.0117	0.0100	0.0098	0.0000	0.1045	0.0219	0.0218
Iso-Levo Pimaric Acid	4.2867	0.1342	0.1883	0.2757	0.0291	0.0997	0.1261	0.0693	0.0094	0.5464	0.2018	0.1691
Dehydroabietic Acid	2.7652	0.0442	0.0203	0.2182	0.0081	0.0221	0.0341	0.0116	0.0000	0.2165	0.0841	0.0345
Abietic Acid	5.5753	0.0509	0.0381	0.2350	0.0039	0.0232	0.0582	0.0259	0.0000	0.4791	0.2765	0.0749
Neoabietic Acid	3.3022	0.0733	0.0846	0.0530	0.0042	0.0134	0.0254	0.0128	0.0016	0.0683	0.0298	0.0298

Table 25: Percent extractives in April 1997 samples												
	1-inside	**1-middle**	**1-outside**	**2-inside**	**2-middle**	**2-outside**	**3-inside**	**3-middle**	**3-outside**	**4-inside**	**4-middle**	**4-outside**
A-Pinene	0.3508	0.1483	0.1214	3.3612	0.1576	0.0863	4.2204	0.1026	0.1822	1.3019	0.1220	0.4411
Camphene	0.0040	0.0022	0.0019	0.0552	0.0019	0.0009	0.0656	0.0011	0.0032	0.0178	0.0015	0.0082
B-Pinene	0.2242	0.1219	0.0984	0.2320	0.0089	0.0196	0.9677	0.0216	0.0335	0.5048	0.0472	0.0444
Myrcene	0.0282	0.0160	0.0139	0.1257	0.0062	0.0020	0.1503	0.0038	0.0073	0.0915	0.0085	0.0219
Limonene	0.0104	0.0053	0.0053	0.0388	0.0019	0.0011	0.0705	0.0026	0.0101	0.0811	0.0072	0.0123
Fenchyl Alcohol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0008	0.0000	0.0000	0.0033
Borneol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0013	0.0000	0.0000	0.0041
4-Allylanisole	0.0314	0.0219	0.0288	0.1618	0.0093	0.0018	0.2129	0.0265	0.0035	0.1159	0.0311	0.0057
Methyl Eugenol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.0000
Pimaric Acid	0.2271	0.0164	0.0125	0.1599	0.0121	0.0104	0.3088	0.0149	0.0509	0.1006	0.0105	0.0714
Iso-Levo Pimaric Acid	0.2413	0.1560	0.0876	0.8468	0.1135	0.0445	1.5379	0.0892	0.0193	1.1203	0.1280	0.0356
Dehydroabietic Acid	0.0687	0.0419	0.0745	0.4921	0.0476	0.0380	0.5459	0.0341	0.0252	0.5833	0.0279	0.0353
Abietic Acid	0.1280	0.0539	0.0352	0.7198	0.0217	0.0273	0.5058	0.0185	0.0361	0.4058	0.0198	0.0772
Neoabietic Acid	0.0578	0.0264	0.0156	0.1829	0.0218	0.0108	0.3052	0.0194	0.0055	0.1631	0.0179	0.0148
	5-inside	**5-middle**	**5-outside**	**6-inside**	**6-middle**	**6-outside**	**7-inside**	**7-middle**	**7-outside**	**8-inside**	**8-middle**	**8-outside**
A-Pinene	0.8298	0.2463	0.0443	0.3055	0.1573	0.3003	1.0552	0.2542	0.0296	0.4878	0.1063	0.3230
Camphene	0.0098	0.0030	0.0012	0.0038	0.0023	0.0040	0.0136	0.0034	0.0003	0.0057	0.0013	0.0094
B-Pinene	0.1143	0.0323	0.0235	0.4098	0.1640	0.0342	0.1631	0.0394	0.0080	0.2498	0.0512	0.2341
Myrcene	0.0494	0.0190	0.0006	0.0104	0.0051	0.0092	0.0360	0.0092	0.0000	0.0076	0.0016	0.0072
Limonene	0.0131	0.0032	0.0047	0.0268	0.0108	0.0166	0.0593	0.0142	0.0013	0.0126	0.0027	0.0508
Fenchyl Alcohol	0.0000	0.0000	0.0009	0.0000	0.0000	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0063
Borneol	0.0015	0.0000	0.0011	0.0000	0.0000	0.0006	0.0000	0.0000	0.0001	0.0000	0.0000	0.0064
4-Allylanisole	0.0137	0.0103	0.0015	0.0169	0.0112	0.0024	0.0277	0.0120	0.0007	0.0241	0.0125	0.0098
Methyl Eugenol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002
Pimaric Acid	0.1720	0.0066	0.0095	0.1984	0.0800	0.0179	0.0921	0.0167	0.0414	0.0364	0.0093	0.0034
Iso-Levo Pimaric Acid	0.5012	0.1433	0.0326	0.3528	0.1346	0.0694	0.6400	0.1813	0.0169	0.4048	0.1138	0.0228
Dehydroabietic Acid	0.2616	0.0519	0.0100	0.1114	0.0727	0.0480	0.2309	0.0293	0.0101	0.0831	0.0203	0.0004
Abietic Acid	0.2695	0.0356	0.0160	0.0881	0.0397	0.0624	0.1720	0.0484	0.0199	0.1190	0.0370	0.0142
Neoabietic Acid	0.0881	0.0185	0.0175	0.1666	0.0623	0.0144	0.0986	0.0311	0.0049	0.0674	0.0201	0.0092
	9-inside	**9-middle**	**9-outside**	**10-inside**	**10-middle**	**10-outside**	**11-inside**	**11-middle**	**11-outside**	**12-inside**	**12-middle**	**12-outside**
A-Pinene	1.8199	0.2503	0.1165	0.8105	0.1514	0.2363	0.8695	0.1118	0.0462	1.2385	0.2069	0.2634
Camphene	0.0410	0.0039	0.0017	0.0105	0.0019	0.0041	0.0123	0.0015	0.0004	0.0165	0.0028	0.0057
B-Pinene	1.7626	0.1703	0.0162	0.1825	0.0393	0.1033	0.4392	0.0485	0.0184	0.5150	0.0707	0.0244
Myrcene	0.0483	0.0061	0.0013	0.0156	0.0030	0.0053	0.0236	0.0027	0.0009	0.0326	0.0058	0.0126
Limonene	0.2082	0.0229	0.0163	0.1150	0.0190	0.0094	0.0274	0.0029	0.0009	0.0298	0.0052	0.0036
Fenchyl Alcohol	0.0040	0.0000	0.0004	0.0000	0.0000	0.0012	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Borneol	0.0041	0.0000	0.0005	0.0000	0.0000	0.0014	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4-Allylanisole	0.0557	0.0047	0.0011	0.0108	0.0116	0.0038	0.0282	0.0051	0.0015	0.0523	0.0205	0.0145
Methyl Eugenol	0.0022	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0006	0.0000
Pimaric Acid	0.1417	0.0726	0.0182	0.1247	0.0068	0.0113	0.0478	0.0064	0.0019	0.0881	0.0081	0.0051
Iso-Levo Pimaric Acid	0.4583	0.0758	0.0241	0.3879	0.1520	0.0219	0.5707	0.0831	0.0200	1.0781	0.1122	0.0315
Dehydroabietic Acid	0.1839	0.0647	0.0215	0.3237	0.0379	0.0062	0.1476	0.0117	0.0075	0.4509	0.0342	0.0123
Abietic Acid	0.3179	0.0495	0.0222	0.2198	0.0377	0.0280	0.2765	0.0296	0.0125	0.6083	0.0550	0.0154
Neoabietic Acid	0.2077	0.0288	0.0036	0.0465	0.0186	0.0069	0.1108	0.0138	0.0042	0.1966	0.0180	0.0064

Table 26: Percent extractives in May 1997 samples												
	1-inside	**1-middle**	**1-outside**	**2-inside**	**2-middle**	**2-outside**	**3-inside**	**3-middle**	**3-outside**	**4-inside**	**4-middle**	**4-outside**
A-Pinene	1.4370	0.1102	0.0874	2.2704	1.2634	0.0829	3.3482	0.0723	0.0668	0.9389	0.1393	0.1004
Camphene	0.0311	0.0011	0.0010	0.0636	0.0648	0.0009	0.0883	0.0006	0.0008	0.0122	0.0017	0.0012
B-Pinene	0.6219	0.0725	0.0673	0.2551	0.3342	0.0027	1.0193	0.0160	0.0151	0.2762	0.0453	0.0308
Myrcene	0.1221	0.0092	0.0089	0.1430	0.1945	0.0024	0.1629	0.0019	0.0021	0.0417	0.0083	0.0060
Limonene	0.0669	0.0029	0.0022	0.0388	0.0527	0.0003	0.1154	0.0006	0.0008	0.0440	0.0062	0.0046
Fenchyl Alcohol	0.0134	0.0000	0.0000	0.0000	0.0000	0.0000	0.0181	0.0000	0.0000	0.0000	0.0000	0.0000
Borneol	0.0168	0.0000	0.0000	0.0009	0.0050	0.0000	0.0225	0.0000	0.0000	0.0000	0.0000	0.0000
4-Allylanisole	0.0816	0.0150	0.0234	0.1451	0.2334	0.0035	0.1076	0.0070	0.0139	0.0246	0.0079	0.0162
Methyl Eugenol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pimaric Acid	0.4614	0.1012	0.0154	0.1232	0.0729	0.0115	0.1104	0.0057	0.0068	0.0682	0.0168	0.0125
Iso-Levo Pimaric Acid	0.5158	0.1003	0.0991	0.5799	0.3522	0.0895	0.4213	0.0560	0.0707	0.3398	0.1199	0.1043
Dehydroabietic Acid	0.2584	0.0340	0.0120	0.3732	0.0874	0.0009	0.2071	0.0016	0.0038	0.2261	0.0400	0.0144
Abietic Acid	0.9058	0.0221	0.0245	0.4739	0.1586	0.0128	0.4591	0.0061	0.0110	0.5360	0.0415	0.0189
Neoabietic Acid	0.2522	0.0187	0.0153	0.1201	0.2080	0.0139	0.1146	0.0116	0.0139	0.0960	0.0175	0.0152
	5-inside	**5-middle**	**5-outside**	**6-inside**	**6-middle**	**6-outside**	**7-inside**	**7-middle**	**7-outside**	**8-inside**	**8-middle**	**8-outside**
A-Pinene	0.6786	0.1681	0.1243	0.2420	0.0951	0.1192	1.3686	0.6235	0.1723	1.6118	0.0864	0.0674
Camphene	0.0099	0.0018	0.0013	0.0068	0.0013	0.0017	0.0203	0.0095	0.0022	0.0237	0.0011	0.0005
B-Pinene	0.0778	0.0226	0.0113	0.0984	0.0971	0.1090	0.1311	0.0785	0.0271	0.7867	0.0426	0.0300
Myrcene	0.0311	0.0103	0.0086	0.0014	0.0030	0.0037	0.0430	0.0200	0.0059	0.0292	0.0011	0.0007
Limonene	0.0145	0.0015	0.0011	0.0240	0.0071	0.0066	0.0823	0.0359	0.0087	0.0430	0.0019	0.0014
Fenchyl Alcohol	0.0027	0.0000	0.0000	0.0055	0.0000	0.0000	0.0043	0.0012	0.0000	0.0000	0.0000	0.0000
Borneol	0.0041	0.0000	0.0000	0.0072	0.0000	0.0000	0.0065	0.0018	0.0000	0.0000	0.0000	0.0000
4-Allylanisole	0.0095	0.0025	0.0058	0.0079	0.0042	0.0061	0.0093	0.0083	0.0081	0.0741	0.0059	0.0090
Methyl Eugenol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pimaric Acid	0.0491	0.0151	0.0155	0.0284	0.0189	0.0211	0.0644	0.0561	0.0212	0.0505	0.0138	0.0117
Iso-Levo Pimaric Acid	0.2770	0.1186	0.1359	0.1940	0.1223	0.1510	0.2750	0.2394	0.0134	0.2820	0.0973	0.0863
Dehydroabietic Acid	0.1538	0.0373	0.0173	0.0000	0.0406	0.0316	0.1679	0.1394	0.0267	0.1175	0.0176	0.0079
Abietic Acid	0.2579	0.0415	0.0235	0.0756	0.0228	0.0262	0.2695	0.1917	0.0356	0.1768	0.0328	0.0224
Neoabietic Acid	0.0920	0.0168	0.0168	0.1052	0.0484	0.0695	0.0632	0.0479	0.0212	0.0545	0.0171	0.0139
	9-inside	**9-middle**	**9-outside**	**10-inside**	**10-middle**	**10-outside**	**11-inside**	**11-middle**	**11-outside**	**12-inside**	**12-middle**	**12-outside**
A-Pinene	1.3350	0.4423	0.2710	0.2415	0.1002	0.1141	0.7749	0.5316	0.0832	1.1435	0.1781	0.1445
Camphene	0.0322	0.0128	0.0043	0.0026	0.0011	0.0013	0.0118	0.0108	0.0009	0.0160	0.0023	0.0018
B-Pinene	0.6970	0.1885	0.1909	0.0554	0.0250	0.0311	0.3628	0.3503	0.0336	0.4485	0.0737	0.0455
Myrcene	0.0222	0.0068	0.0068	0.0033	0.0018	0.0023	0.0179	0.0191	0.0020	0.0283	0.0042	0.0037
Limonene	0.1818	0.0625	0.0288	0.0346	0.0134	0.0133	0.0272	0.0294	0.0018	0.0277	0.0042	0.0031
Fenchyl Alcohol	0.0206	0.0102	0.0000	0.0000	0.0000	0.0000	0.0017	0.0036	0.0000	0.0000	0.0000	0.0000
Borneol	0.0215	0.0111	0.0000	0.0000	0.0000	0.0000	0.0020	0.0042	0.0000	0.0000	0.0000	0.0000
4-Allylanisole	0.0330	0.0118	0.0044	0.0052	0.0043	0.0133	0.0151	0.0122	0.0047	0.0277	0.0104	0.0150
Methyl Eugenol	0.0000	0.0004	0.0015	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pimaric Acid	0.0668	0.0282	0.0449	0.0241	0.0112	0.0132	0.0479	0.0552	0.0093	0.0743	0.0219	0.0198
Iso-Levo Pimaric Acid	0.2473	0.0948	0.2203	0.1459	0.0806	0.1189	0.2683	0.2374	0.0727	0.4376	0.2176	0.1496
Dehydroabietic Acid	0.1129	0.0024	0.0337	0.0603	0.0268	0.0172	0.1797	0.0906	0.0138	0.1965	0.0395	0.0272
Abietic Acid	0.2972	0.0559	0.0484	0.0410	0.0211	0.0228	0.3971	0.1376	0.0278	0.4273	0.0876	0.0602
Neoabietic Acid	0.1420	0.0512	0.0066	0.0212	0.0100	0.0156	0.0755	0.0609	0.0128	0.0988	0.0332	0.0228

HIGHLIGHTS

Our major accomplishment was the finding that low-headspace RF pre-treatment of lumber extracts over 80% of the VOCs while leaving most of the water in the wood. Thus, RF energy is not used to evaporate water, but only to maintain the wood at constant temperature. The mechanism of this extraction is not fully understood. We hypothesize that since the water cannot escape from the wood, it "pumps" out the VOCs. Work on developing a theoretical framework for this has just been initiated. If the headspace from the extractor is passed through hot silicone oil, the VOCs can be removed without condensing the steam. Condensation would require disposal of the condensate, which would be an added cost, since most facilities are permitted as zero discharge.

Two configurations are being considered for commercialization. First, an RF pre-treatment unit can precede a conventional drying kiln. In this configuration, the lumber would be fed through a belt device which is typically a part of most industrial RF dryers. The VOC-depleted lumber can then be dried conventionally, i.e. without modifying the existing dryers. In the second, the RF unit and the kiln would be combined, and the RF would be used only during initial drying. We tentatively prefer the first arrangement, and are presently working on designing the entire assembly and estimating capital costs. Operating power costs will be low, but an estimate is deferred until the capital costs are established. We emphasize that the costs of operating our RF extractor will be much lower than that of an RF dryer, since water is <u>not</u> evaporated in our arrangement.

RF is the only low-headspace VOC-extraction option available for lumber, since heating with other means such as steam is far too time consuming. However steam is adequate for smaller furnishes such as particle, OSB or veneer, where either RF or steam can be used. For now, we have established feasibility; optimization and development of the economics will follow.

Removal of VOCs from wood without extracting the water requires an understanding of the transport of these materials through wood. Hence, the effect of furnish size, geometry, and the importance of surface and edge effects were studied, and clearly pointed out why RF was the only real option for lumber, whereas either RF or steam could be utilized for the smaller furnishes. Finally, an extensive study of seasonal effects of VOC concentrations in wood has been initiated. In previous work we have found up to a fourfold seasonal dependence of VOC emissions. However, corresponding changes in the terpene content of wood is only of the order of 40%. A comprehensive controlled study of the terpene and resin/fatty acid content in a targeted set of trees is underway, and will be continued for a year. These data will establish how and why stack emissions vary across the seasons.