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Wood Influence on Thermomechanical Pulp Quality.
Part 1: Fiber Separation and Fiber Breakage

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Wood Influence on Thermomechanical Pulp Quality:

Part 1. Fiber Separation and Fiber Breakage

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ABSTRACT

Refining experiments were carried out on slow-growing, average-density and plantation-grown, low-density loblolly pines. The logs were debarked, chipped, and refined at the Andritz pilot plant using a 36-1CP refiner. Three sets of identical refiner plates were obtained for the trial. One set was used as manufactured. The second set had the fine bar section removed, and the third set had the fine bar section and half of the intermediate bar section removed. Primary pulps from the full plates and intermediate section plates were also second-stage refined in a Bauer 401 atmospheric refiner.

Analysis of the wood particle breakdown patterns indicates that the generation of the pass 14-mesh Bauer McNett fraction, decrease in shives, and changes in Bauer McNett fractions all follow a first-order comminution model. This shows a faster rate of wood breakdown for the low-density sample. The low-density wood also gives a faster generation of the R_{28} long fiber fraction, but it does not survive secondary refining. By the time the pulp has reached a freeness level typical of newsprint grade TMP, the pulp produced from the low-density wood has shorter average fiber length and less R_{14} and R_{28} than the pulp produced from the average-density wood.

INTRODUCTION

In recent years, many TMP and groundwood mills have struggled with changes in the wood supply that result in lower strength pulp. In the southeast, the shift from forest-grown wood to lower density plantation-grown sources has usually resulted in reductions in tear strength but with an increase in opacity.[1,2] In the northwest, a shift to more second growth timber has had similar effect.[3] This has also resulted in a shift from preferred species like spruce to less desirable species like hemlock and lodgepole pine. These changes are challenging for the mills because product specifications have become more demanding with shifts to lower basis weights and higher brightness targets. In an effort to gain a better understanding of what causes the strength and optical changes from these transitions, a project was initiated to evaluate fundamental differences in refining performance and bonding characteristics of TMP produced from various wood sources. Selected for the project a traditional forest-grown southern pine and a lower density, plantation-grown southern pine to supply a high juvenile content wood source.

Wood is not a uniform material, and differences in fibril angle and cell wall thickness[4] both influence the strength of fibers.[5,6] Recent research has shown that in subjecting loblolly pine wood to cyclic compression (simulating a disk refiner), nearly all the compressive strain and viscoelastic energy absorption occurs in the earlywood portion of the annual growth ring.[7,8] The results suggest that earlywood is much more intensively stressed under the initial refining conditions than is the latewood. The implication of this is that in mechanical pulping processes, the earlywood will disintegrate faster and suffer more fiber damage than latewood. This was confirmed by analyzing chlorite holopulped fibers from the various particle sizes produced after very low energy pressurized refining.[9] In this research, the smaller particles, those retained on the 20- and 100-mesh screens, had a lower fiber coarseness and more earlywood fibers than the fibers in the particles retained on the 4- and 8-mesh screens. In addition, the smaller particle size fractions contained fewer whole fibers, and there was a lower percentage of whole earlywood fibers than whole latewood fibers in all the size fractions.

The uneven energy absorption in the early stages of refining fragments the earlywood fibers.[7] This makes them less able to contribute to the strength of the product and results in both wasted energy and a weaker paper. Because Douglas-fir and the southern yellow pines contain large amounts of latewood, and the difference between the specific gravity, elastic modulus, and tensile strength of the earlywood and latewood is very large,[5,6] these species suffer acutely from the concentration of refining energy in the earlywood and produce low strength mechanical pulps.[10,11]

Since changes in the ratio of earlywood and latewood, and the strength difference between the earlywood and latewood are the most obvious changes encountered with the changes in wood supply, this effect on refining was of primary interest. To evaluate wood breakdown into fiber during disk refining, the development of single fibers and fiber fractions was measured and comminution rates determined for the development and degeneration of the 14-, 28- and 48-mesh fractions of the Bauer McNett.

Particle comminution theories have been used to describe wood disintegration in refining before. Yan used a first-order kinetic model to evaluate changes in average fiber length and particle width in pressurized and atmospheric refiners.[12] Kano *et al.* used a three-step model (fiber bundles, single fibers, and broken fibers) in an attempt to determine the energy of fiberization for TMP and RMP.[13] In an effort to build improved models for refiner control, Strand and Mokvist selected a comminution model consisting of both a selection function and a breakage parameter to describe size reduction in refining.[14] They concluded that the breakage parameters were fairly constant in refining, but the selection function was influenced by chemical treatment and the operating conditions of the refiners.[14] The comminution analysis in this research has been carried out using a first-order approach and has been evaluated as a single rate process for the reduction in the R_{14} mesh fraction, a single rate process for the reduction in Pulmac 0.25 mm shives, and a six rate process evaluating the reduction and formation of the R_{14}, R_{28}, R_{48}, and P_{48} mesh fractions.

EXPERIMENTAL

Two wood samples were obtained for the project, a fast-grown plantation pine of low density, and a forest-grown sample of average density. Wood parameters are summarized in Table 1 below. On average, the final growth ring of the low-density pine was the only one with a high level of latewood, indicative of mature wood character. The average-density wood typically had 7 to 10 years of high latewood-content growth rings.

Table 1: Wood characterization (density is in OD weight per green volume).

Wood	Density g/cc	Latewood	Ring Width	Age
Average-density Pine	0.49	40.4%	4.2	13.8
Low-density Pine	0.41	30.2%	9.1	6.2

The wood was debarked, chipped, and refined at the Andritz Pilot Plant in Springfield, OH. Samples were prepared using full-size refiner plates, pattern D14B001 (herein referred to as whole plates), similar plates with the fine bar section removed (Intermediate), and plates with both the fine bar and half of the intermediate sections removed (Small). Primary refining was carried out in a Sprout-type 36-1CP pressurized refiner operating at 2000 rpm. Primary pulps from the full plates and intermediate plates were second-stage refined in a Bauer 401 atmospheric refiner. Specific energy consumption, freeness and pulp fractionation are summarized in Table 2.

Table 2. First stage specific energy applications and pulp properties.

Wood	Plate Type	Specific Energy GJ/ton	Freeness mL	Shives %	Fines %	14 Mesh	28 Mesh	48 Mesh
Average-density	Whole	3.5	679	14.5	21.7	15.5	22.6	19.9
Low-density	Whole	3.3	757	16.8	16.3	18.3	33.2	18.2
Average-density	Interm.	1.5	762	46.2	21.8	39.4	18.7	11.1
Low-density	Interm.	1.1	768	47.4	16.6	41.5	21.4	12.1
Average-density	Small	0.9	777	61.9	4.7	59.6	17.1	10.2
Low-density	Small	0.7	780	40.4	6.6	43.4	21.6	15.3

HANDSHEET ANALYSIS

Fully refined pulp properties were as expected. The average-density pine gave a tear index of 5.6 $mN{\bullet}m^2/g$ with 18.9 Nm/g tensile index at 7.2 GJ/ODMT (2.0 MWh/ODMT). The low-density pine gave a tear index of 4.9 $mN{\bullet}m^2/g$ and tensile index of 16.3 Nm/g at a specific refining energy of 7.2 GJ/ODMT (2.0 MWh/ODMT). A graph of tensile index relative to specific energy consumption is shown in Figure 1. This shows about a 15% loss in tensile index when using the low-density wood source.

The refiner plates without the fine bar section gave much poorer pulp quality than the whole plates. For whole plates, TMP fiber length was about 3% longer for the pulps produced from the average-density wood. TMP produced with the intermediate size plates gave fiber lengths about 10% lower than the pulps produced with whole plates. First-stage specific energy and basic fiber properties are summarized in Table 2.

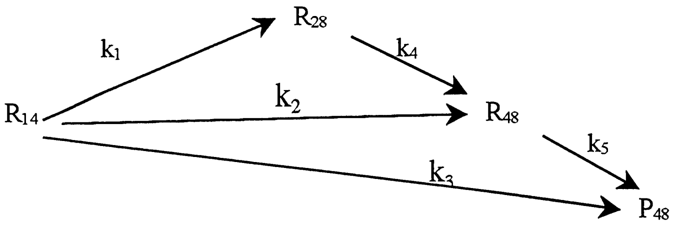
COMMINUTION ANALYSIS

The R_{14} mesh fraction breaks down by three processes, which occur in parallel, giving R_{28}, R_{48}, and P_{48} mesh fractions. There is also a series process consisting of the R_{28} fraction breaking down into R_{48}, which, in turn, breaks down into P_{48}. A second series process of R_{28} breaking down into P_{48} has been ignored because it will contribute relatively little to the understanding of the process and greatly complicates the rate equations and estimation of the rate constants.

If k is the first-order rate of disappearance of the R_{14} mesh fraction, k_1 is the first-order rate at which R_{14} forms R_{28}; k_2 is the rate at which R_{14} forms R_{48}; and k_3 is the first-order rate at which R_{14} forms the pass 48 mesh (P_{48}) fractions, the series process abides by the following equality:

$$k = k_1 + k_2 + k_3$$

The other disintegration rates contributing to the fragmentation process are k_4, the rate at which R_{28} breaks down into R_{48}, and k_5, the rate at which R_{48} breaks down to form P_{48}. Again, the process $R_{28} \rightarrow P_{48}$ has not been considered because this would be difficult to distinguish from k_4 and k_5. Using E for the specific energy consumption, the rate equations for the amount of material in each of the four fractions are shown below. Derivation of these expressions follows simple first-order kinetics.



$$R_{14} = e^{-kE}$$

$$R_{28} = \frac{k_1}{k_4 - k}\left(e^{-kE} - e^{-k_4E}\right)$$

$$R_{48} = \frac{k_2}{k_5 - k}\left[e^{-kE} - e^{-k_5E}\right] + \frac{k_4 k_1}{(k_4 - k)(k_5 - k)}\left[e^{-kE} - e^{-k_5E}\right] - \frac{k_4 k_1}{(k_4 - k)(k_5 - k_4)}\left[e^{-k_4E} - e^{-k_5E}\right]$$

$$P_{48} = 1 - R_{14} - R_{28} - R_{48}$$

Analysis of R_{14}

A first-order comminution abides by the equation $\ln(R_{14}) = k\Delta E + \ln(C_o)$. For the disappearance of the R_{14} fraction, C_o is 1 and this term drops out. Plotting $\ln(R_{14})$ against SEC should give a straight line relationship with slope = -k and intercept of 0 (Figure 2). The resulting constants for R_{14} reduction are given in Table 3, along with the r^2 for the regression analysis. Also summarized in Table 3 is the rate of reduction of 0.25-mm Pulmac shives and the initial rate of reduction in R_{14} estimated in the four-fraction analysis. In this case, the initial constant is adjusted to match the rate of formation of R_{28}, R_{48} and P_{48}. For this reason, results differ slightly.

In general, the three methods of analysis give similar results. The rate of wood breakdown is in the range of 0.47 to 0.85 ODMT/GJ using both the full plates and the plates with the fine bar section removed. The rate of wood breakdown is 5% faster for the low-density wood based on the disappearance of shives, and 15% faster based on the reduction in R_{14}.

Table 3: First-order wood disintegration rates using R_{14} and shives.

Wood	Plates	Four Fraction Analysis	R_{14} Data k (ODMT/GJ)	r^2	Shive Data k (ODMT/GJ)	r^2
Average-density	Whole	0.639	0.474	0.92	0.677	0.95
Average-density	Intermediate	0.694	0.756	0.86	0.715	0.92
Low-density	Whole	0.519	0.566	0.94	0.703	0.95
Low-density	Intermediate	0.694	0.849	0.91	0.758	0.90

Extended Comminution Analysis, R_{14}, R_{28}, R_{48}, and P_{48}

The rate equations for formation and breakdown of the four Bauer McNett fractions were solved manually by entering the equations in a spreadsheet and adjusting each k iteratively. The root mean squared deviation was used as the fit parameter. The resulting comminution constants and final RMSE for each case are given in Table 4. An example of the formation and reduction of the Bauer McNett fractions for the low-density pine refined using the whole refiner plates is shown in Figure 3. The lines show the calculated fractions based on the comminution rates.

The cases for the whole plates and the plates with the fine bar section removed (intermediate plates) both contain the data from the smallest plates (with both the fine bar and half the intermediate bar sections removed). Generally, the results from the first stage refining with the fine bar section removed did not fit well with the results from the whole plates, so these data were not included in the analysis for the whole plates. The most significant deviations from the model all occur at low energy. This may be due to difficulties in obtaining good energy measurements under these conditions, but is more likely due to the physical constraints of the initial chip breakdown in refining. Because wood chips cannot fit between the refiner plates, there is a massive amount of chip destructuring that must take place before the wood chips pass through the breaker bar section of the refiner.

Table 4: Comminution rate constants, units are ODT/GJ.

	R_{14}	14->28	14->48	28->48	14->P_{48}	48->P_{48}	RMSE
	k	k_1	k_2	k_4	k_3	k_5	
Low W	0.519	0.305	0.094	0.186	0.119	0.222	0.038
Low I	0.694	0.389	0.092	0.389	0.214	0.361	0.041
Avg W	0.639	0.222	0.128	0.064	0.289	0.053	0.048
Avg I	0.694	0.278	0.147	0.194	0.269	0.200	0.068

Low is low-density pine; Avg is average-density pine. W and I are for the whole and intermediate refiner plates.

The pattern of wood breakdown into individual fibers and fiber fragments is slightly faster using the intermediate plates. Besides higher rate constants, this also shows up as a 10-point loss in long fiber (R_{28}) and a 30% loss in tear and is consistent with an increase in refining intensity. The differences in the patterns of wood breakdown between wood sources are quite informative. The average- and low-density pine break down at similar rates, but the average-density generates less long fiber (k_1) and more broken fiber (k_2) and P_{48} mesh (k_3) material in the initial parallel breakdown process. For the low-density pine, the rates in the series breakdown process (or secondary refining) are much faster. The value of k_4 for the low-density pine is three times that of the average-density wood, and the value of k_5 for the low-density pine is four times that of the average-density pine. The pulps produced with the intermediate plates are similar. Low-density pine generates more long fiber in the primary refining, but it does not survive the secondary refining process, and at usable freeness levels, the pulps produced using the low-density pine have less long fiber and shorter average fiber length than the TMP produced from the average-density material.

These results are consistent with the theory presented in the introduction. The low-density pine should have less latewood than the average-density wood. Therefore, energy should be concentrated in the smallest volume of material in the average-density pine, and dispersed over a larger volume of material in the low-density pine. Higher energy concentration in the average-density wood should result in a faster initial generation of small particles and fines. The larger volume of earlywood in the low-density wood should distribute the energy over a larger number of fibers, and generate more long fiber. In this analysis, the initial rate for generation of P_{48} material (k_3) when using the whole plates is 0.289 ODT/GJ for average-density wood and 0.119 for low-density material. Using the intermediate plate data, k_3 for average-density at 0.268 ODT/GJ is also larger than for the low-density wood at 0.214. According to the theory, the earlywood is eventually destroyed in the refining process, and the remaining long fiber is predominately latewood. Indeed, the rate of secondary refining is faster for the low-density pine as the earlywood fibers liberated initially are broken later in refining. An interesting feature of the low-density pine is that with the high initial rate of development for R_{28}, and high rate of secondary refining of R_{28} to R_{48}, there is a pronounced maximum in the R_{28} curve (Figure 3). This is an indication that there are either weak fibers or considerable damage to the long fiber fraction in the early stages of refining. It also suggests that lower intensity refining might improve results with the low-density wood. Andritz has also reported improved refining of plantation wood with the RTS process.[15]

CONCLUSIONS

Wood type and refining conditions are found to create distinct differences in the rates at which fibers are liberated from the chip mass and broken in the refining process. Generally, the total coarse wood mass (R_{14}) breaks down at nearly the same rate for the wood sources evaluated, but at slightly different rates for the two refiner plate sizes. Average-density pine develops the long fiber fraction at a slower rate than low-density pine, but also gave less long fiber reduction in extended refining than found with the low-density wood source. This results in the decrease in long fiber normally observed when refining plantation-grown pine. These results are consistent with the theory that refining energy is concentrated in the earlywood portion of the annual growth ring. The lower amount of earlywood in the average-density pine should result in greater localized refining intensity and less long fiber as observed. However, earlywood fibers rarely survive refining without breaking. The long earlywood fibers that survived the first stage refining of low-density pine are broken in the second stage resulting in the low average fiber length.

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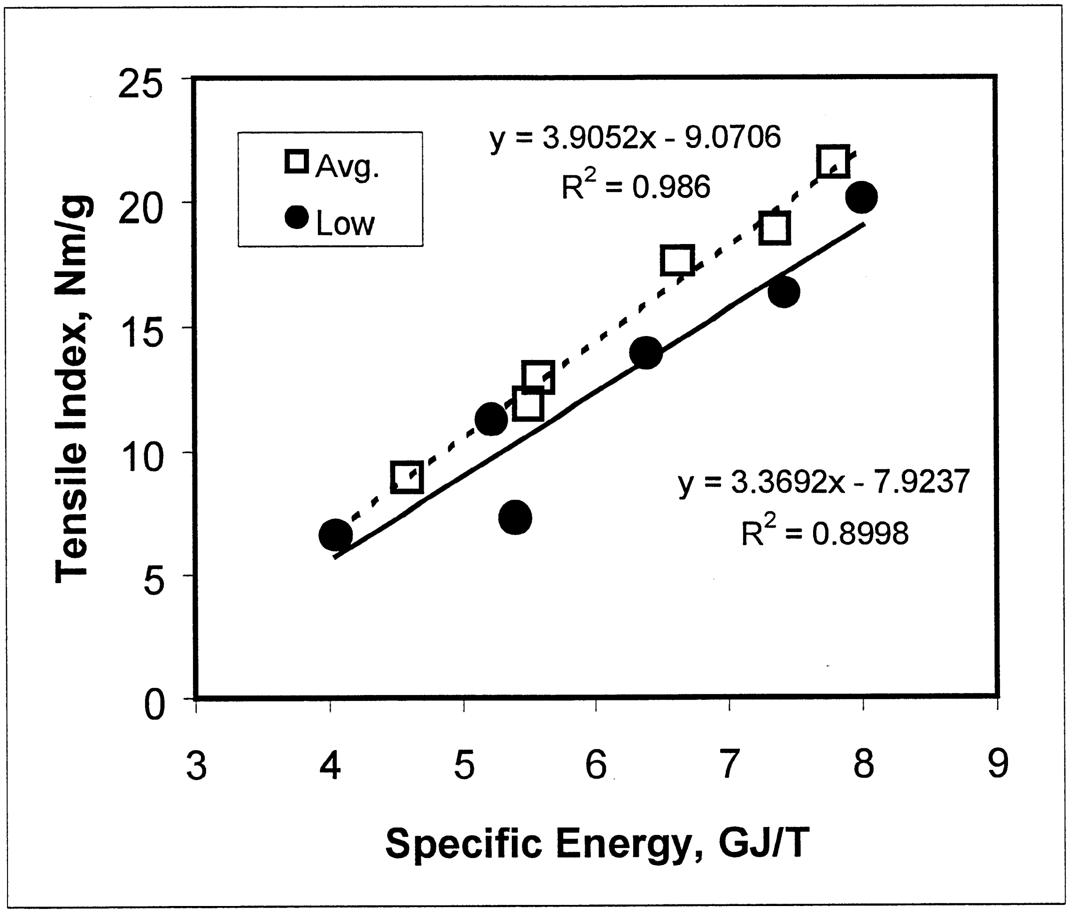

Figure 1. Tensile Index relative to Specific Energy Consumption. The TMP produced from low-density pine gives low tensile strength.

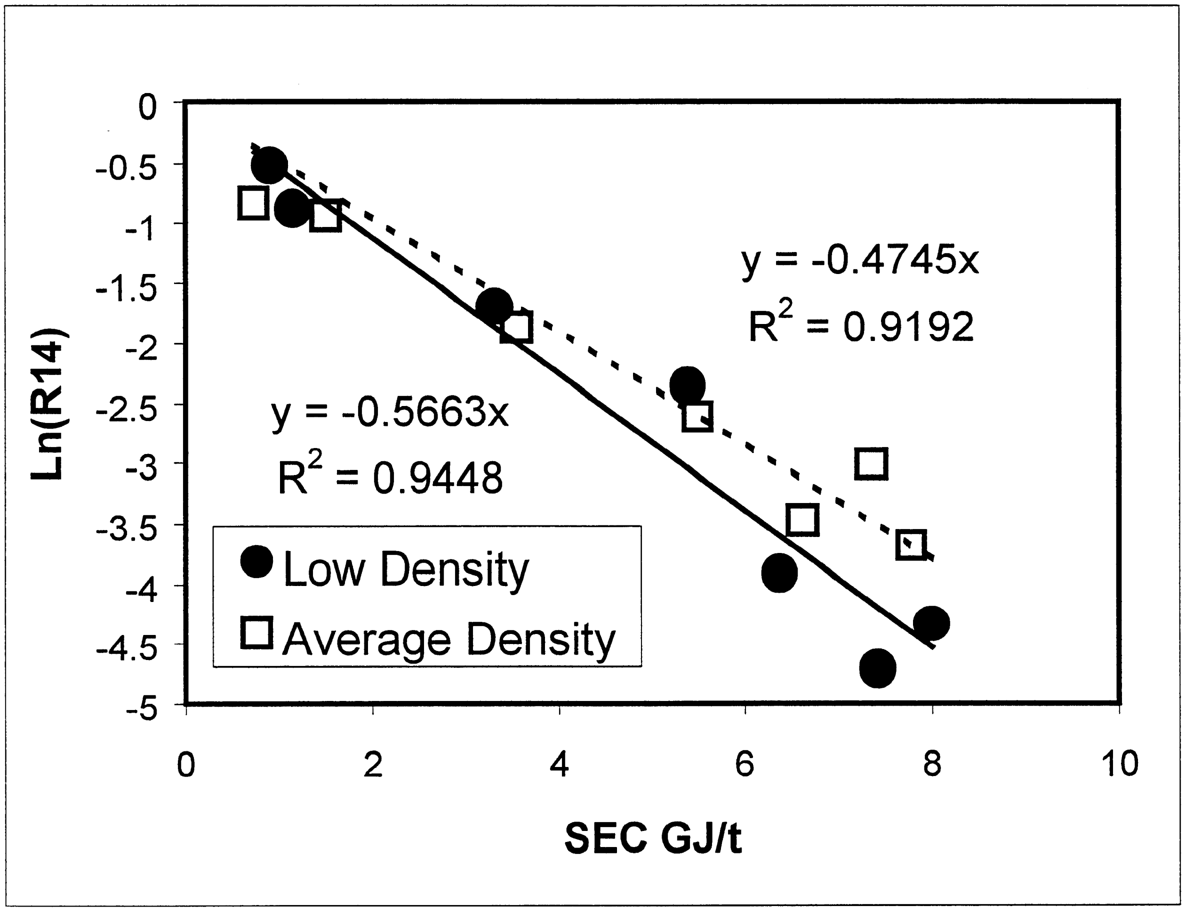

Figure 2. R14 reduction with specific energy.

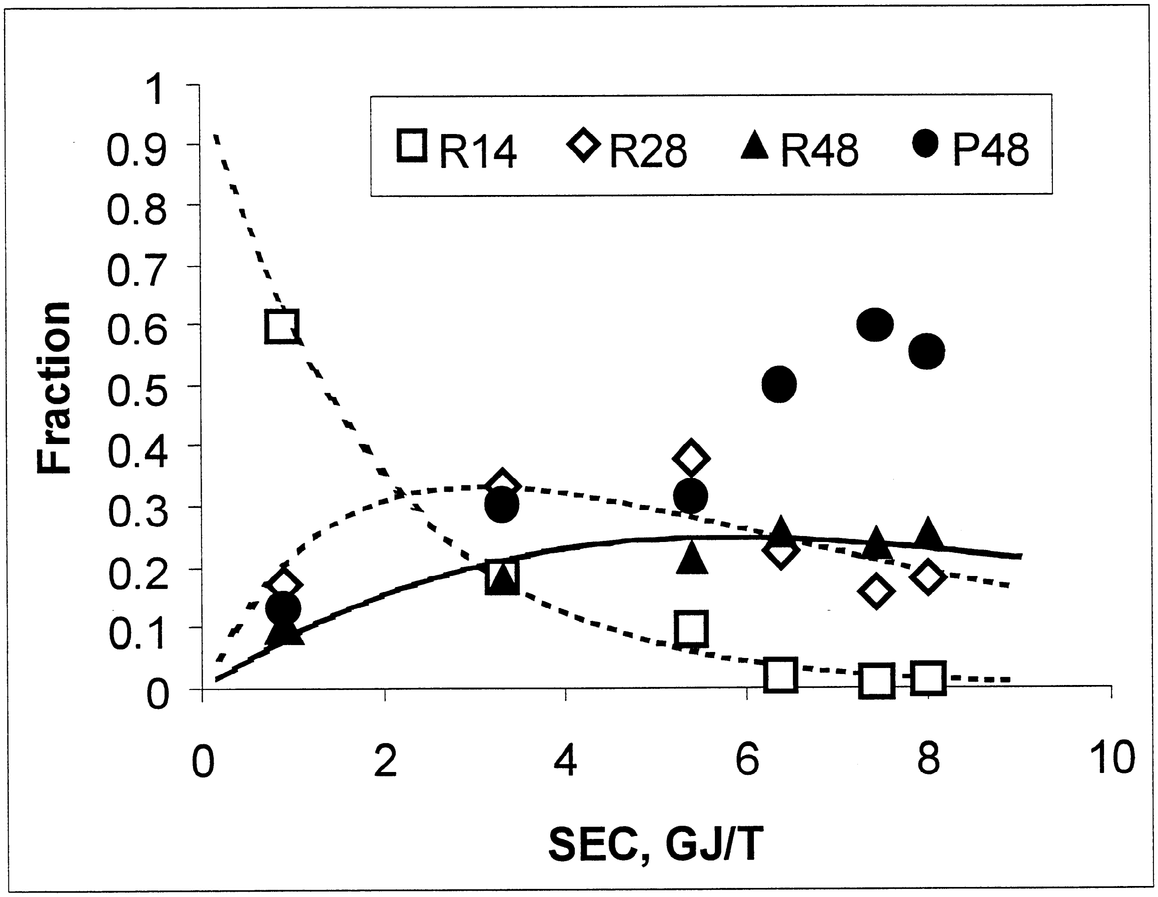

Figure 3. Change in Bauer McNett fractions of the low-density pine using the whole refiner plates.