MICROWAVING LOGS FOR ENERGY SAVINGS AND IMPROVED PAPER PROPERTIES FOR MECHANICAL PULPS

C. Tim Scott
John Klungness

USDA Forest Service
Forest Products Laboratory
One Gifford Pinchot Drive
Madison, WI 53726–2398

Mike Lentz
Eric Horn
Masood Akhtar

Biopulping International
2403 Industrial Drive
Madison, WI 53713

ABSTRACT

High-power microwave cooking of commercial black spruce pulpwood logs was investigated as a pretreatment for mechanical pulping. Several dozen logs were treated at a variety of power levels (10 to 50 kW) and for various times (1 to 10 min). The mechanical pulping trials resulted in significant energy savings-up to 15% for the highest power level. In addition, there was a corresponding increase in handsheet properties (+35% burst index, +20% tear index, and +13% tensile index) and a modest reduction in brightness (–10%). Handsheets were made to simulate a lightweight coated furnish, and microwave-treated thennomechanical pulp was used to supplement a reduction in the kraft component. Based on handsheet properties, as much as 10% kraft pulp could be substituted with only slight reductions in strength. Annual pulp cost savings were estimated for an 800 ton/day pulp mill based on anticipated kraft substitution levels, refiner energy savings, and microwave pretreatment costs.

INTRODUCTION

Of the world's total wood-based pulp production for the year 2000, 37 million metric tons (22%) were from mechanical pulps and 130 million metric tons (78%) were from chemical or semi-chemical pulps [1]. Clearly, chemical pulps are preferred for a variety of paper grades, generally for better strength as a result of superior pulp quality (e.g., higher freeness, higher fiber length, and lower lignin content). However, chemical pulps are expensive to produce and fiber yields are generally very low (about 50%). On the other hand, mechanical pulps have fiber yields in excess of 90%, but pulp quality is degraded because fiberization is sometimes not complete and fibers can be severely damaged. Each process has its own inherent advantages and disadvantages, and papermakers must weigh these factors when developing a furnish for a particular paper grade. However, faced with the reality of more restrictive environmental regulations, increased energy costs, competitive pricing, and a more diverse raw wood resource, papermakers are being forced to be more creative in selecting furnish components. Therefore, efforts must be made to develop new technologies that improve the quality of mechanical pulps, making them more attractive as a component in higher quality paper grades.

In thennomechanical pulping (e.g., thermomechanical pulping [TMP] and chemi-thermomechanical [CTMP]), high power refiners are used to mechanically reduce wood chips to fiber. To aid in this process, elevated temperatures are used to soften the wood. Several refining "passes" are generally required to obtain a target freeness. The first pass is usually defibration at temperatures above 100°C and immediately below or at the glass transition temperature. of lignin (T_g < 124°C). During this pass, chips are typically fiberized under pressure using an aggressive plate pattern to produce a high freeness pulp. This pulp is then further reduced in multiple passes through an atmospheric refiner until the desired pulp freeness is obtained. Because each refining pass requires substantial electrical power input, maintaining controlled operating conditions, such as feed rate and consistency, is essential to optimize pulp quality and minimize total energy use.

Microwaving of logs as a pretreatment to pulping is a revolutionary new approach to improving paper quality. Research at Oak Ridge National Laboratories and North Carolina State University [2] showed that for chemical (kraft) pulping, microwave pretreatment of wood decreased the alkali requirement, increased the screened yield by about 2%, and reduced the reject level. This study also demonstrated that significantly larger chips could be used since the penetration rate of the liquor is much higher for microwave-pretreated wood. There was evidence that for hardwoods, microwave pretreatment increased permeability by breaking the pit membranes and vessel cell ends caused by steam pressure, thereby enhancing the diffusion of pulping chemicals into the wood.

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Previous literature on the microwaving of wood has been primarily confined to chemical pulping processes or drying of lumber. We studied the effects of microwave treatment on whole logs to improve mechanical pulping, specifically TMP, to reduce energy consumption, and to improve pulp quality. We hypothesized that steam pressure would build up inside the logs during microwaving, altering the lignin (possibly through depolymerization) and softening the wood Subsequent fiberization and refining would occur more easily and fiber damage would be reduced. The following report describes an exploratory investigation of the effects of microwave pretreatment on the mechanical pulping characteristics of commercial black spruce logs.

EXPERIMENTAL

Based on previous studies, availability, and common use as a species for TMP, black spruce (*Picea mariana*) logs were selected for microwave pretreatment and pulping. About 60 commercial pulpwood logs (culled for uniformity) were obtained, each 1.2 m long, 15 to 20 cm in diameter, and as "green"as possible (preferably about 40% moisture content). These logs were shipped to the pilot facility of MICRODRY, INC., a manufacturer of custom industrial microwave ovens.

A high capacity microwave oven was recommended for initial tests (Fig. 1). This oven is connected to a variable-power (up to 60 kW) 915-MHz frequency generator. A continuous belt transport system that can accommodate logs up to 30 cm in diameter was available, but it was not used since the treatment timing was unknown. Instead, individual logs were manually placed in the microwave chamber. Various treatment levels were investigated based on power setting (20 to 50 kw) and exposure time (1 to 10 min). After treatment, selected logs were weighed and the temperature profile was measured at three radial positions (near the pith, near the bark, and about halfway between). At the conclusion of the trials, all treated logs were individually shrink-wrapped and shipped to the Forest Products Laboratory (FPL) for further processing.

At FPL, each log was cut in half before chipping. A 5-cm disk was removed from the middle for visual analysis. After soaking in water for 24 h to re-hydrate, the logs were debarked and chipped, producing about 200 L (one 55-gallon barrel) of chips per treatment. Two preliminary TMP fiberization trials were undertaken to establish a suitable pulping protocol. This protocol incorporated an initial TMP fiberization pass to obtain a target freeness of 750 mL Canadian Standard Freeness (CSF), followed by four subsequent atmospheric refining passes to attain 550,350,200, and 100 mL CSF, respectively. Power consumption was measured for each refiner pass. Refining conditions selected for all TMP trials are shown in Table 1.

Samples of microwave pretreated TMP (MwTMP) were blended at various substitution levels with bleached softwood kraft market pulp (BLSW) and groundwood (GW) aspen market pulp to simulate a typical lightweight coated (LWC) furnish. A 50% BLSW/27.5% TMP/22.5% GW blend was chosen as the base pulp. TAPPI standard handsheets (T205) were prepared from all pulp samples generated in the refining trials and from LWC blends. The handsheets were tested for burst (T403), tear (T414), and tensile properties (T494) as well as diffuse brightness (T525). Based on refiner energy savings, property improvements, and operational cost estimates for a microwave pretreatment facility, an attempt was made to calculate annual pulp cost savings for an 800 ton/day mill producing LWC paper grade with MwTMP substituted for some BLSW.

Table 1. Refining conditions for processing TMP pulps

Process		Plate type[a]	Target freeness (mL)	Plate gap (mm)	Speed (r/min)	Feed rate (g/min)	Solids content (%)
Pressurized fiberization (200 kPa)		D2B505	750	0.737	3000	550	50
Atmospheric refining	1st pass	C2976	500	0.457	3000	550	6
	2nd pass		350	0.127	3000	550	6
	3rd pass		250	0.102	3000	550	6
	4th pass		100	0.089	3000	550	6

[a]Both plates were Durametal plates.

RESULTS

Microwave Treatments and Observations

Several combinations of power levels and exposure times were investigated on a trial and error basis, The first log was microwaved for 3 min at 35 kW. In about a minute, the log split and steam began to blow from each end. As the test progressed, splitting and steaming became more pronounced. After 3 min, the log was removed from the chamber and a thermocouple was inserted into each of three predrilled holes to measure the radial temperature profile. The temperature of the pith was measured at 102.8°C; the temperature in the middle was 99°C and that near the bark was 73°C (initial log temperature was 11.6°C). A second log was microwaved for 1.5 min at 50 kW. Again, the log began to split in about a minute and steam jetted from the ends. At 1.5 min, the log was removed from the chamber and the temperature profile was measured (pith, –107°C; bark, –84.3°C). A third log was microwaved for 4 min at 20 kW. This time no splitting or steam generation occurred, and the temperature gradient was small (pith 99.9°C to bark 93.7°C). Several other combinations of power level and exposure time were explored. In general, higher power levels resulted in higher log temperatures, with steeper temperature gradients from bark to pith (Fig. 2).

Of particular interest were the logs microwaved for 5 min at 50 kW. Within a couple of minutes, splitting became intense and steam jets shot out the ends of the logs (Fig. 3). In just 5 min, the logs had lost about 25% of their weight or nearly all of their moisture. A visual examination of the ends of the logs revealed extensive radial checking (Fig. 4). A dye penetration test was attempted, but it was ineffective. We unanimously decided that, at the risk of burning the logs, the 5-min/50-kW treatment was the most reasonable maximum power level for the remaining trials. Of the 60 logs available for treatment, 10 logs were used to explore various power levels and about 15 logs were treated at the 5-min/50-kW level.

Several fracture surfaces from logs treated at 5 min/50 kW were sampled to identify possible morphological changes in the fiber structure. A scanning electron microscope was used to obtain images of both tangential and radial surfaces (Figs. 5 and 6). Surprisingly, there was no indication of fractures in the torus, as had been observed in hardwoods [2]. What became apparent, however, is that the fracture surfaces were very "clean," with little evidence of fiber splitting. This observation seems to indicate that stress fractures caused by steam pressure propagated through the middle lamella without damaging the cell wall, as is normally observed on fracture surfaces.

Mechanical Pulping of Microwave–Pretreated Logs

Two exploratory mechanical pulping trials were run with chips from control logs and logs microwave treated at 5 min/50 kW. The first trial was a 4-pass reduction to 100 mL CSF in an atmospheric refiner (see refining conditions in Table 1). The total energy required for treated chips (2,051 W·h/kg) was significantly lower (about 15%) than that of the control chips (2,411 W·h/kg). Handsheets made from these pulps also indicated a dramatic improvement in mechanical properties (+18% tear index, +21% tensile index, and +36% burst index) with a corresponding reduction (–10%) in brightness. These results were very encouraging, but the refining protocol was not realistic because it produced an inferior pulp. The second trial incorporated initial TMP fiberization, followed by four atmospheric refining passes to 100 mL CSF. Again, microwave pretreatment reduced the refiner energy requirement by 15% and handsheets properties exhibited a similar trend (+17% tear index, +21% tensile index, +35% burst index, and –11% brightness).

Based on the results of the exploratory mechanical pulping trials, it was evident that microwave pretreatment can substantially lower refiner energy requirements while improving pulp quality. To verify this, a more extensive evaluation was undertaken using the logs that were microwave pretreated at several different power levels. The logs were debarked and chipped, then refined by the established TMP protocol to produce MwTMP. Figure 7 shows pulp freeness as a function of total refining energy for the last three atmospheric refining passes, indicating total energy savings for all microwave pretreatments. Of particular interest is the relationship of increased energy savings to increased microwave power levels (Fig. 8). Handsheets made from these pulps also exhibited an increase in mechanical properties, with only moderate reductions in brightness (Table 2). As with total energy reduction, an increase in mechanical properties seems to correlate with an increase in microwave power level (Fig. 9).

Table 2. Properties of TAPPI handsheets produced from microwave-preheated black spruce TMP

Trial	Power level	Burst index		Tear index		Tensile index		Brightness		Density
	(kW·h)	(kN/g)	(%)	(mN·m²/g)	(%)	(Nm/g)	(%)	(%)	(%)[a]	(kg/m³)
Control	0	1.26	0	4.07	00	27.4	0	56.0	0	401
3 min, 35 kW	1.75	1.41	11.90	4.31	5.90	29.4	7.30	53.8	−3.93	415
4 min, 20 kW	1.33	1.31	3.97	4.19	2.95	302	10.22	55.1	−1.61	405
6 min, 20 kW	2.00	1.67	32.54	4.75	16.71	30.9	12.77	50.9	−9.11	417
3 min, 50 kW	1.25	1.37	8.73	4.51	10.81	29.0	5.84	51.0	−8.93	410
5 min, 50 kW	4.17	1.70	34.92	4.88	19.90	31.0	13.14	50.7	−9.46	415

[a]Percentage of change from control value.

Blends With Kraft Pulp

The strength improvements shown in Table 2 suggest that it may be possible to substitute MwTMP for kraft pulp in an LWC furnish. In producing handsheets, the BLSW component was reduced by 5% and 10% and replaced with an equivalent increase in the TMP/GW component (maintaining a 55% TMP/45% GW ratio). Additionally, the TMP component (control pulp) was entirely replaced by MwTMP (Table 3). The TMP/GW and MwTMP/GW components also required moderate bleaching to achieve a brightness of 74%. Selected material properties were measured on handsheets made from each blend (Table 3). These results show that only moderate reductions in strength result from a 5% kraft substitution when the MwTMP component is unbleached. However, if the MwTMP component is bleached, an increase in strength is observed at the 5% substitution level, with only a moderate decrease in strength at the 10% substitution level.

Table 3. Handsheet properties of LWC blends

Handsheet composition (%)				Power level[a]	Chelated + bleached	Burst index		Tear index		Tensile index		Brightness		Density
BLSW	GW	TMP	MwTMP	(kW·h)	(% H_2O_2)	(kN/g)	(%)	(mN·m²/g)	(%)	(Nm/g)	(%)	(%)	(%)[b]	(kg/m³)
50	22.5	27.5	0	0	0	2.11	0	9.71	0.0	37.4	0.0	65.8	0	559
45	25	0	30	2	0	2.02	-4.3	9.65	-0.6	36.9	-1.3	64.4	-2.1	564
45	25	0	30	4.17	0	2.08	-1.4	9.69	-0.2	37.2	-0.5	64.6	-1.8	562
50	22.5	27.5	0	0	1.5	2.23	0	9.9	0	39.5	0	73.9	0	553
45	25	0	30	4.17	1.5	2.39	7.2	10.23	3.3	40.4	2.3	72.9	-1.4	544
40	27	0	33	4.17	1.5	2.17	-2.7	9.67	-2.3	37.0	-6.3	72.0	-2.6	521
45	25	0	30	4.17	2	2.41	8.1	10.29	3.9	40.5	2.5	74.1	0.3	528
40	27	0	33	4.17	2	2.16	-3.1	9.69	-2.1	37.2	-5.8	74.1	0.3	517

[a]Total microwave energy transmitted to log (PF = 4.17 for 5 min at 50 kW, PF = 2 for 6 min at 20 kW).
[b]Percentage of change from control value.

A preliminary analysis of pulp costs was undertaken to determine the economic feasibility of incorporating microwave log pretreatment in the TMP pulping protocols for an LWC furnish. Two possible scenarios were evaluated: (a) microwave pretreatment at 20 kW for 6 min and (b) microwave pretreatment at 50 kW for 5 min. In scenario (a), 10% total refiner energy savings, or about $9/ton (based on $0.031 kW·h), would be realized. However, this savings would be more than offset by an increase in bleaching cost (about $2/ton) and microwave pretreatment costs (about $15/ton), for a net increase of about $8/ton. Total pulp cost for MwTMF' is estimated to be about $253/ton. However, pulp quality is also improved, and the kraft component can be reduced and replaced by MwTMP. Since the kraft component is more expensive, an overall saving in total pulp cost can be realized, depending on the cost of BLSW and its substitution level.

Figure 10 shows estimated total pulp cost savings for an 800 ton/day mill. In scenario (b), 15% refiner energy savings, or about $14/ton, can be realized. This is more than offset by an increase in bleaching costs ($3/ton) and microwave treatment costs ($29/ton), for a total pulp cost of $263/ton. Again, because pulp quality is improved, the kraft component can be further reduced, with a resultant savings in total pulp cost (Fig. 10). An estimate of capital costs for 20-kW and 50-kW systems could range from $7.5 to $12.5 million.

CONCLUSIONS

This study was undertaken to explore the possibility of using microwave pretreatment to alter the structure of wood such that fiberization occurs more easily during mechanical pulping, thereby reducing refiner energy requirements and improving the pulp. All treatments seemed to quickly heat the logs. At the highest power levels, the treatments generated considerable steam pressure, which caused extensive internal fracturing. However, microscopic analysis showed little indication that the pit membranes had been ruptured, as was anticipated. The most severe log damage and moisture loss were caused by the 50-kW/5-min treatment,

Significant energy savings were realized for the microwave-pretreated logs. The highest energy savings (15%) corresponded to the highest power levels used. Handsheet strength properties were also increased (up to 35%) with increasing power level, but at a reduction in brightness (–10%). The microwave treatments may have caused lignin depolymerization (either by resonance or high temperatures), which led to the refiner energy savings. This seems to be supported by the observation that fractures in the treated logs occurred predominately through the middle lamella. However, it is unknown whether these treatments caused an unexpected change in fiber morphology during fiberization and refining that improved handsheet properties.

The combination of refiner energy savings and improved handsheet properties (excepting brightness) seemed to indicate that microwave-pretreated thermomechanical pulp (MwTMP) may be an acceptable substitute for some kraft in a lightweight coated (LWC) pulp furnish. Increasing the bleached groundwood aspen market pulp MwTMP component by 5% improved properties significantly. At the 10% addition level, properties were only slightly below that of the control pulp. A substantial annual savings in pulp cost can be realized if MwTMP is substituted for kraft in an LWC furnish.

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2. Jameel, H., Chang, H., Compere, A., and Griffith, B., “Microwaving of Logs to Increase Yield and Decrease Chemical Usage”, proceedings from the 2001 TAPPI Pulping Conference, Seattle, Washington.

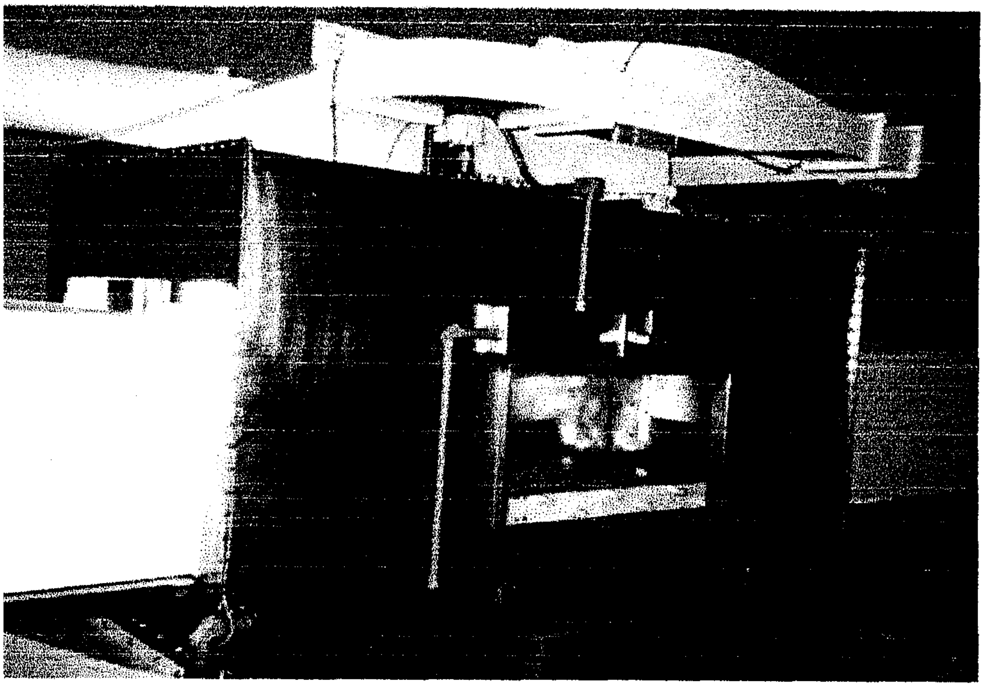

Figure 1—Waveguide and chamber for 60-kW industrial microwave oven.

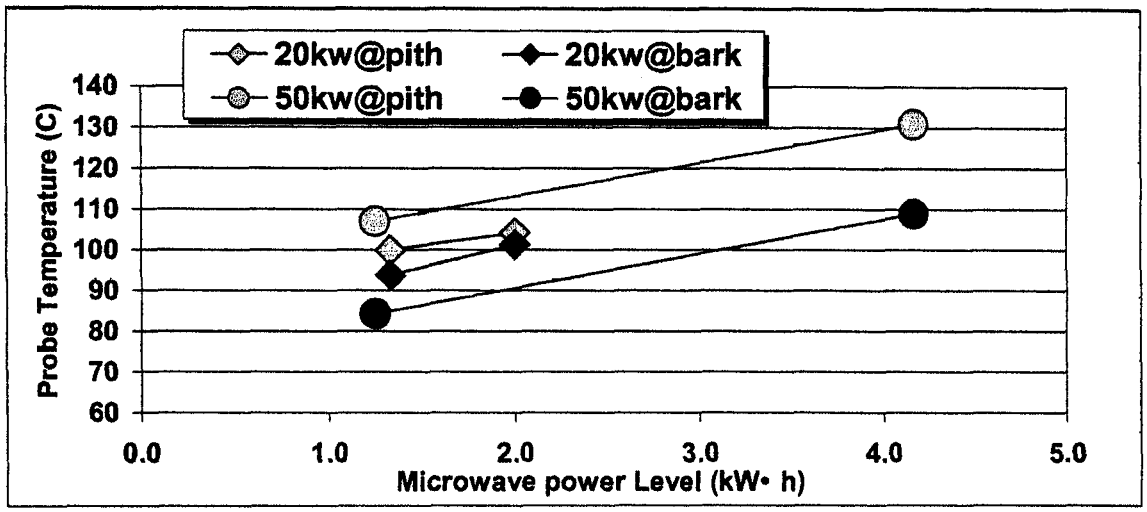

Figure 2—Radial temperature profile as a function of power level for 20- and 50-kW treated logs.

Figure 3—Steam jet issuing from end of log after microwave treatment at 50 kW for 5 min.

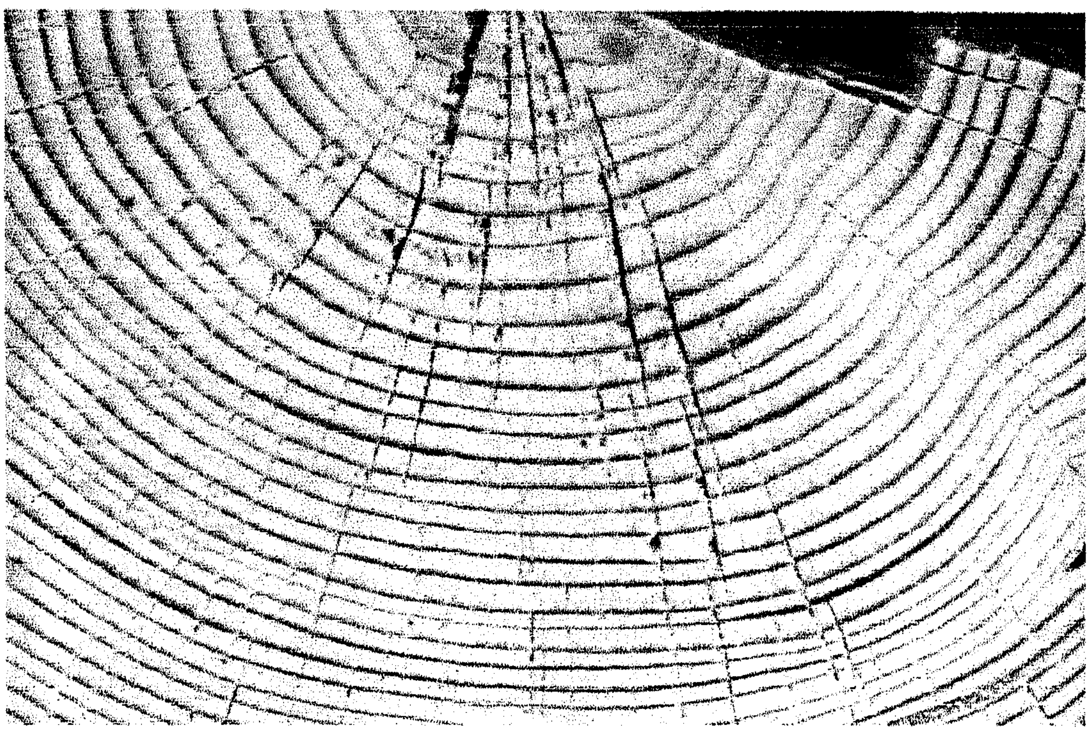

Figure 4—Extensive radial checking observed after microwave treatment at 50 kW for 5 min.

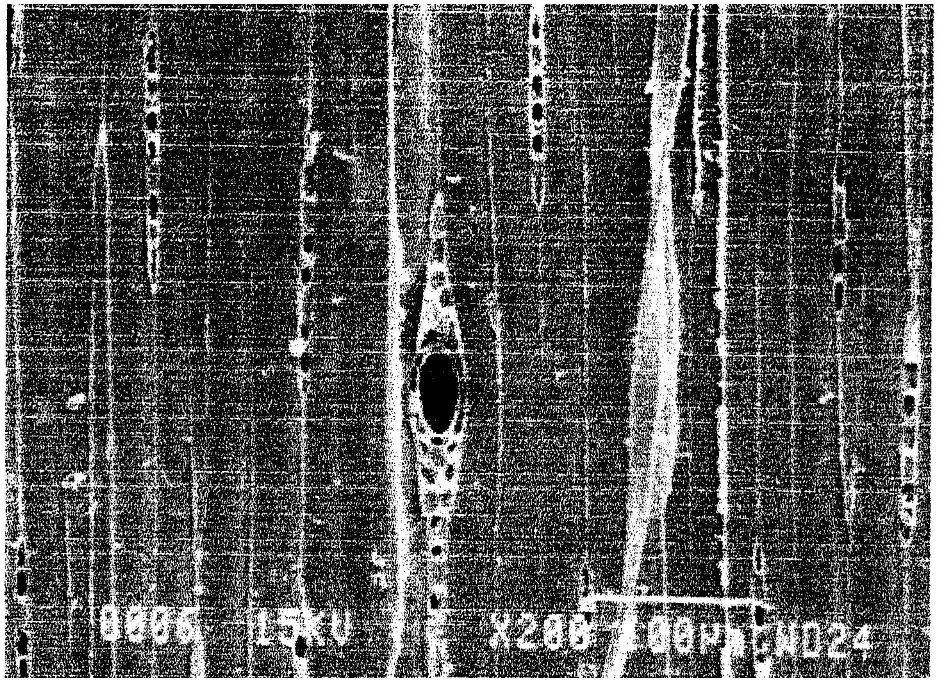

Figure 5—SEM of tangential fracture surface after microwave treatment at 50 kW for 5 min.

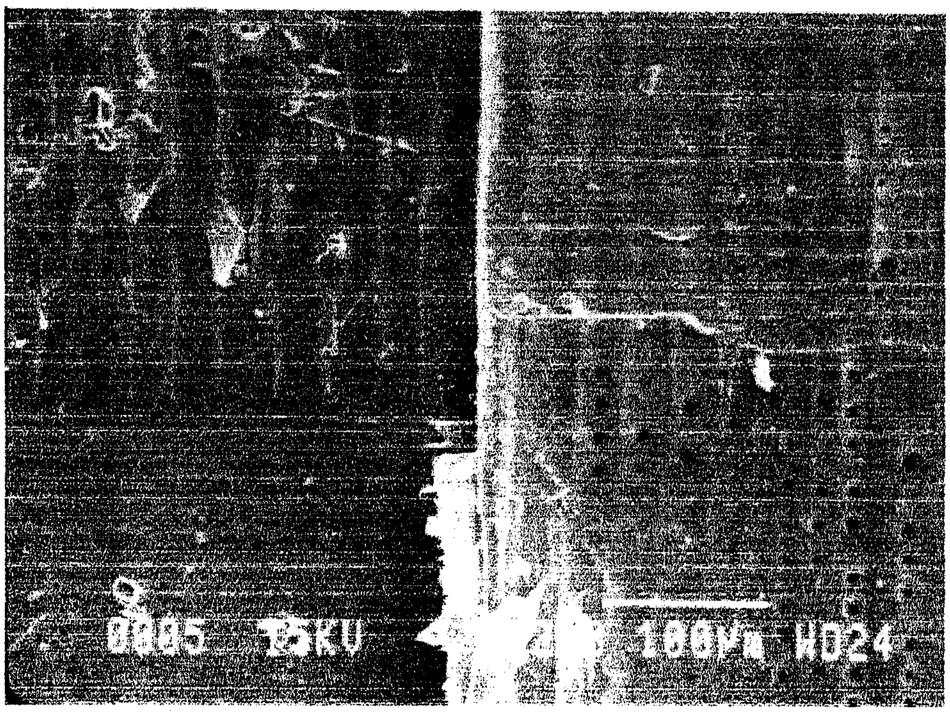

Figure 6—SEM of radial fracture surface after microwave treatment at 50 kW for 5 min.

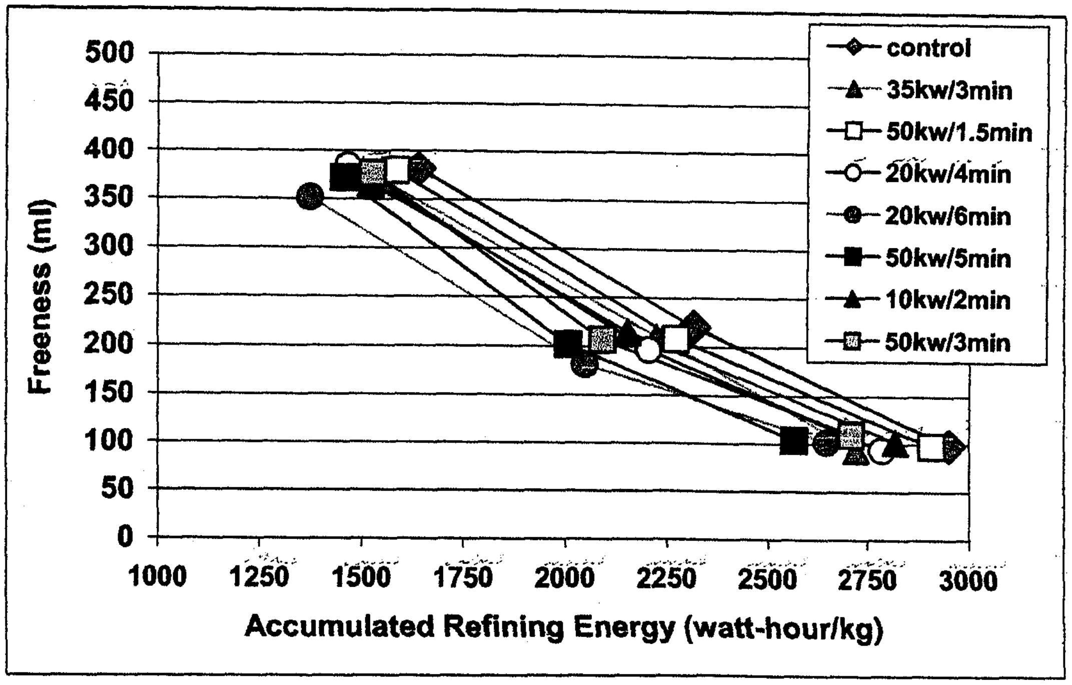

Figure 7—Freeness as function of refiner energy consumption for various microwave pretreatments.

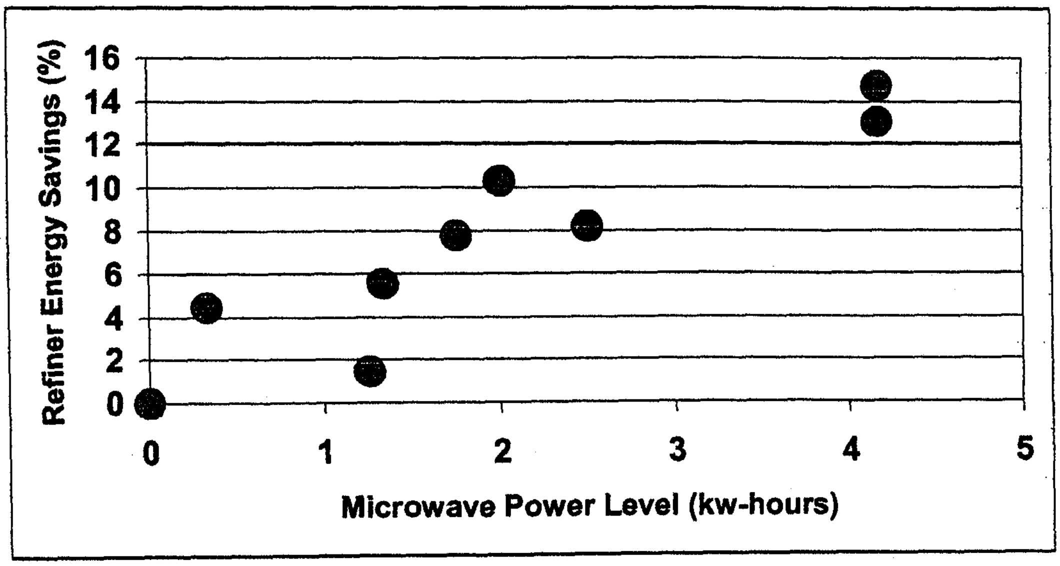

Figure 8—Refiner energy savings relative to microwave power level for variety of pretreatments.

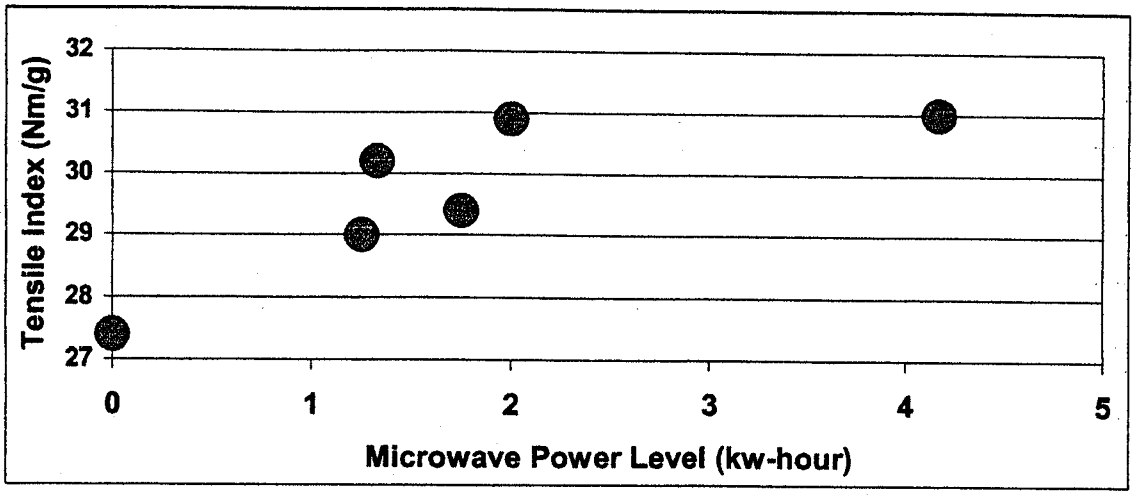

Figure 9—Tensile index as function of power level for microwave pretreated black spruce TMP.

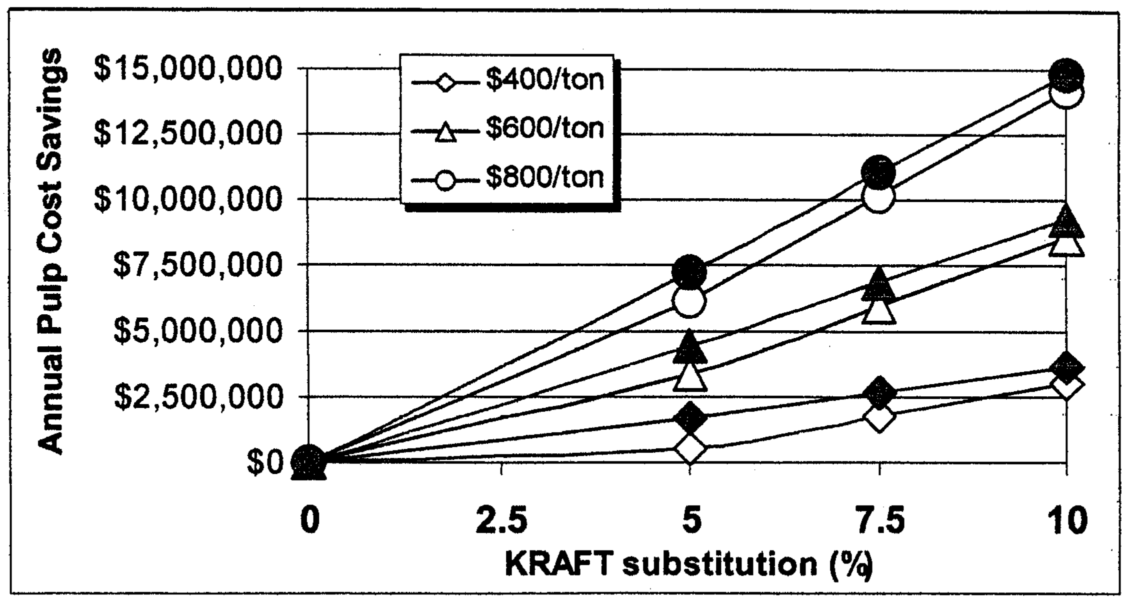

Figure 10—Estimated annual pulp cost savings for 800 ton/day LWC mill based on substituting MwTMP for kraft (closed symbol represents 6 min at 20 kW, open symbol 5 min at 50 kW).