Refining intensity, energy consumption, and pulp quality in two-stage chip refining

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ABSTRACT *Thermomechanical pulps were produced in two pilot plant installations. Both installations were conventional two-stage systems in which the first stage was pressurized and the second was atmospheric. At a given specific energy, pulp quality was improved. Alternatively, for a given pulp quality, the energy consumption was reduced when refining in the first stage was carried out at a high refining intensity. High refining intensity was reached by operating the first stage either at a high rotational speed or low consistency. There were indications that these benefits could be enhanced if the second stage were operated at a low refining intensity.*

KEYWORDS
Chips
Consistency
Energy
Pulp properties
Refining
Thermomechanical pulping

The residence time of the pulp in the refining zone of a chip refiner determines the number of bar impacts imparted to the fibers (*1*). If the specific energy is held constant, the residence time controls the average amount of energy transferred at each impact: this average specific energy per impact is the refining intensity. The concept of refining intensity is that the quality of the pulp will depend not only on the specific energy applied but also on the intensity with which it is applied.

The residence time and the refining intensity can be calculated from the equations derived for the flow of pulp in a chip refiner under a variety of operating conditions (*1*). These equations have been applied to the results of experiments on single-stage atmospheric refining (*2*) and on two-stage thermomechanical pulping (*3*), demonstrating that while the pulp properties vary greatly for the same amount of specific energy, they correlate with the calculated refining intensity. Therefore, the refining intensity is an important variable, as is specific energy, in determining the quality of mechanical pulps.

The pulp flow equations show that for an individual refiner, the refining intensity can be changed in a number of ways, such as by changing the refining consistency, the rotational speed, the steam pressure drop across the refining zone (in a thermomechanical refiner), and the density of bars in the plate pattern. Sundholm, Heikkurinen, and Mannstrom have reported the effect of refiner speed on pulp properties in thermomechanical pulping on a pilot plant refiner (*4*). They kept the rotational speed the same in both stages. Miles has calculated the changes produced in the refining intensity from the pulp flow equations in these experiments and has related these to the change in pulp properties at constant specific energy (*2*).

In a two-stage system, the refining intensity can be changed independently in either stage. Because the nature of the material being refined is different in each stage, a change in refining intensity in one stage could have a different effect on the final pulp properties than the same change made in the other stage. Here, we present a preliminary study of this effect, in which the refining intensity was changed in two pilot-plant thermomechanical pulping systems by varying the rotational speed of the refiners in one system and the consistency in the other.

The effect of rotational speed

Experimental procedures

Pilot plant experiments on the effect of rotational speed were carried out at the Sprout-Bauer laboratory between 1977 and 1981 using black spruce, red cedar, southern pine, and a mixture of black spruce and balsam fir (*5*). The refining conditions are shown in **Table I**.

A pressurized double rotating disc refiner, 914 mm in diameter (Model 418), was used in the first stage and was operated at different fixed speeds between 600 and 1800 rpm. The plate pattern was Type 36104 with subsurface dams; the bar and groove widths were 3.7 mm and 4.9 mm respectively, giving a bar density of approximately 1.2 bars/cm. Second-stage refining was carried out in a 914-mm-diameter, open-discharge refiner (Model 401), operated over the same range of speed. It was equipped with 36106X plates. These plates also had subsurface dams; both bar and groove widths were 4.9 mm, giving a bar

I. Experimental conditions

Species	Solids, %	First-stage refining: Dry bulk density, kg/m³	First-stage refining: Specific energy, GJ/ton	First-stage refining: Speed, rpm*	Second-stage refining: Discharge cons., %	Second-stage refining: Specific energy, GJ/ton	Second-stage refining: Speed, rpm*	Second-stage refining: Discharge cons., %
Black spruce	53	126	3.3-3.7	1200 1800	20-25	0.9-4.6	600 900 1200	10 and 20
Black spruce and balsam fir at a 75:25 mixture	74	145	1.3-4.7	600 900 1200 1800	20-25	1.3-6.0	1200	20
Southern pine	47	183	1.2-4.7	1200 1800	20-25	1.3-4.0	1200 1800	20
Cedar	...	...	3.2	1200	20-21	1.5-4.8	1200 1800	20

*Rotational speed.

II. Properties of first-stage pulps (spruce and balsam)

	A	B_1	B_2	D_1	D_2	D_3	F_1	F_2	F_3	F_4
Specific energy, GJ/ton	2.4	2.1	2.2	1.7	2.4	4.7	1.3	1.8	2.1	2.6
Rotational speed, rpm	600	900	900	1200	1200	1200	1800	1800	1800	1800
Consistency, %	20	26	23	24	22	25	28	22	23	23
Residence time, s	4.37	1.46	1.35	0.47	0.59	1.4	0.12	0.13	0.16	0.20
No. of impacts, thousands	39.33	19.78	18.25	8.46	10.7	26.3	3.36	3.64	4.45	5.35
Specific energy/impact, 10^{-4} GJ/ton	0.61	1.08	1.21	2.02	2.25	1.78	3.82	4.88	4.79	4.92
Specific ref. power, GJ/ton per s	0.57	1.49	1.63	3.62	4.05	3.27	10.30	13.14	12.93	13.29
Freeness, mL CSF	740	724	723	685	668	299	735	693	756	398
L-factor, %	93	91.5	91	74	77	58.5	88	86	72	62
Fines, % (P-100)	2.7	3.3	3.1	21	18	33	4.9	5.9	21	28
Somerville shives, %	59	38	32	8.7	7.1	0.11	44	11	3.7	0.88

density of about 1 bar/cm. Discharge consistency was varied from 20% to 25% in the first stage and from 10% to 20% in the second stage.

Pulps were hot-disintegrated before testing, and pulps and handsheets were evaluated according to TAPPI methods.

Results

The residence time τ, the total number of impacts n, the specific energy per impact e and the specific refining power $\dot{e}$, were calculated for the conditions in these experiments from the pulp flow equations for both stages as described previously (*2*, *3*). The steam flow term in the pulp flow equation was neglected on the assumption that the effects of the forward and backward steam flows on the residence time were equal and cancelled each other out (*2*, *3*). The values of the friction coefficients in the radial and tangential directions were assumed to be 0.25 and 0.75, respectively (*1*).

The total residence time τ_t in both stages, and the total number of impacts n_t were calculated from

$$\tau_t = \tau_1 + \tau_2 \quad (1)$$

and

$$n_t = n_1 + n_2 \quad (2)$$

where the subscripts 1 and 2 refer to the first and second stages. The average specific energy per impact over both stages e_a and the average specific refining power $\dot{e}_a$ were calculated from

$$e_a = E_t/n_t \quad (3)$$

and

$$\dot{e}_a = E_t/\tau_t \quad (4)$$

where

E_t = the total specific energy added over both stages.

The results of the calculations are shown in **Table II**. The effect of rotational speed is immediately apparent. When the speed was increased, for example, from 900 rpm to 1800 rpm at the same specific energy and consistency (2.2 GJ/ton and 23% for Samples B_2 and F_3), the residence time decreased almost 10-fold from 1.35 s to 0.16 s. As a result, the number of impacts decreased from 18,250 to 4450. This drop increased the specific energy per impact from 1.2×10^{-4} GJ/ton to 4.8×10^{-4} GJ/ton. The change in the specific refining power was even

Effects that rotational speed variations in the first stage have on pulp properties

First stage						
E_1, GJ/ton	2.1		2.1		2.1	
Rotational speed, rpm	900		1200		1800	
Consistency, %	26		23		23	
Residence time, s	1.46		0.55		0.16	
No. of impacts, thousands	19.78		9.97		4.45	
e_1, 10^{-4} GJ/ton	1.08		2.13		4.76	
$\dot{e}_1$, GJ ton per s	1.49		3.84		12.93	
Freeness, mL CSF	724		676		756	
Fines, % (P-100)	3.3		19		21	
L-factor, %	91.5		75.5		72	
Shives, %	38		8.0		3.7	
Density, kg/m³	193		233		267	
Tear index, mN•m²/g	7.4		10.7		9.2	
Tensile index, N•m/g	6.9		15.5		20.1	
Scattering coef., m²/kg	30.4		39.3		44.4	
Second stage						
E_2, GJ/ton	3.65	5.0	3.65	5.0	3.65	5.0
E_{total}, GJ/ton	5.75	7.1	5.75	7.1	5.75	7.1
Rotational speed, rpm	1200	1200	1200	1200	1200	1200
Consistency, %	20	20	20	20	20	20
Residence time, s	0.78	1.02	0.78	1.02	0.78	1.02
No. of impacts, thousands	14.02	18.40	14.02	18.40	14.02	18.40
e_1, 10^{-4} GJ/ton	2.59	2.71	2.59	2.71	2.59	2.71
$\dot{e}_2$, GJ/ton per s	4.69	4.90	4.69	4.90	4.69	4.90
Freeness, mL CSF	260	130	150	80	79	38
Fines, % (P-100)	30	34	35	37	38	48
L-factor, %	65	60	60	51	51	41
Shives, %	0.79	0.31	0.22	0.14	0.11	0.07
Density, kg/m³	341	370	384	465	420	500
Tear index, mN•m²/g	11.5	10.7	10.3	8.1	7.8	6.2
Tensile index, N•m/g	38	43	43	47	44	50
Scattering coef., m²/kg	52.0	55.0	62.0	66.0	70.0	76.0

more marked; it increased from 1.6 GJ/ton per s to 13 GJ/ton per s.

The effect of consistency on refining intensity is smaller than the effect of rotational speed. The change in the specific energy per impact is approximately inversely proportional to the change in consistency (*1*). Because the range of consistency was small in these experiments, its effect on the refining intensity was unimportant compared with that of rotational speed.

The specific energy affects the residence time but has little effect on the refining intensity. This is seen by comparing Samples D_1 and D_3 or F_1 and F_4 in Table II. An increase in the specific energy increases the residence time and the number of impacts, but it produces essentially no change in either the specific energy per impact or the specific power per impact. This finding follows directly from the pulp flow equations. The refining intensity in these experiments was therefore governed essentially by the rotational speed.

Properties of first-stage pulps. The first-stage pulp properties are shown at the bottom of Table II. When the refiner speed was doubled from 900 rpm to 1800 rpm and 2.1 GJ/ton of specific energy was applied (Pulps B_1 and F_3), the increase in refining intensity and specific refining power reduced the L-factor by 20%, reduced the shives content by almost 90%, and increased the fines content seven-fold. There was almost no effect on the freeness at this low level of energy.

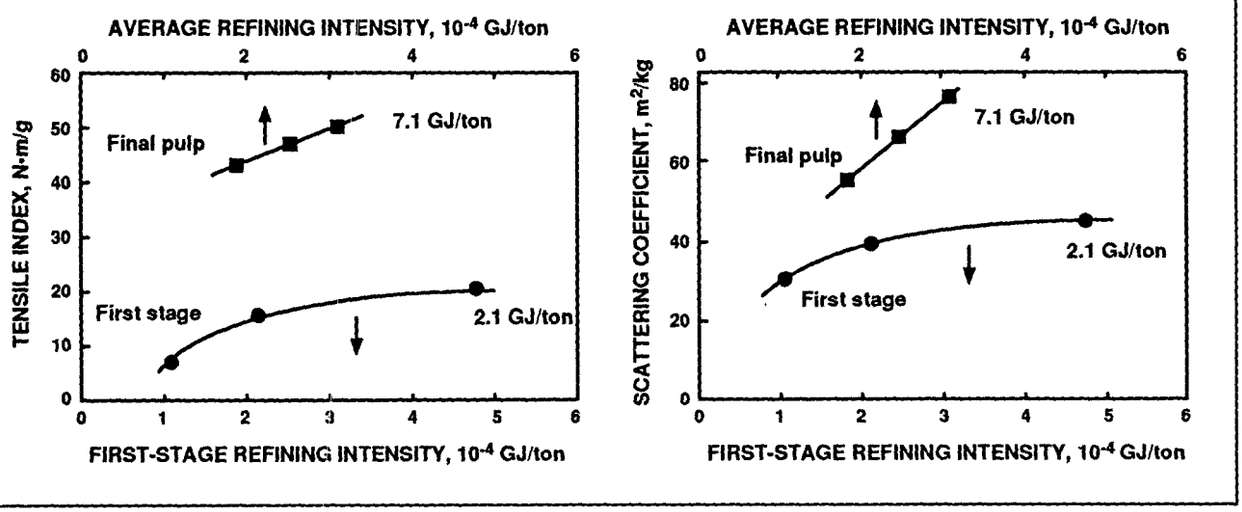
Table III shows the pulp properties at a constant specific energy of 2.1 GJ/ton and at 900 rpm, 1200 rpm, and 1800 rpm. Even at this low energy level, increasing the refining intensity decreases the shives and long fiber content and increases the fines content, the sheet density, the tensile strength and the scattering coefficient. These effects are similar to those reported earlier (*2*).

Overall energy quality relationships. The pulps described were further refined in an open-discharge refiner that operated at 1200 rpm and a discharge consistency of 20%. The refining intensity in the second stage was therefore constant. The pulp properties have been interpolated to two values of applied specific energy, 3.65 and 5.0 GJ/ton, for a total specific energy of 5.75 GJ/ton and 7.1 GJ/ton, respectively. The results are shown at the bottom of Table III. As noted before, the different energy levels produce a change in the residence time and in the number of impacts but

IV. Effects that rotational speed variations in the first stage have on pulp properties (spruce and balsam)

Specific energy, GJ/ton					
E_1	2.4	2.1	1.7	2.4	2.1
E_2	5.6	6.0	4.7	4.8	3.5
E_{total}	8.0	8.1	6.5	7.2	5.6
Rotational speed, rpm					
ω_1	600	900	1200	1200	1800
ω_2	1200	1200	1200	1200	1200
Consistency, %					
C_1	20	26	24	22	23
C_2	20	20	20	20	18
Residence time, s	5.28	2.63	1.45	1.58	0..76
Total no. of impacts, thousands	57.65	41.12	26.25	28.64	15.21
Refining intensity					
e_1, 10^{-4} GJ/ton	0.61	1.08	2.02	2.25	4.79
$\dot{e}_1$, GJ/ton per s	0.57	1.49	3.62	4.05	12.93
$\dot{e}_1/e_1$, s^{-1}	0.93	1.38	1.79	1.80	2.70
e_a, 10^{-4} GJ/ton	1.39	1.97	2.47	2.53	3.69
$\dot{e}_a$, GJ/ton per s	1.49	3.06	4.48	4.62	7.39
Freeness, mL CSF	73	83	83	95	93
Fines, % (P-100)	53	56	51	56	55
L-factor, %	38	36	41	36	36
Shives, %	0.18	0.20	0.13	0.18	0.12
Density, kg/m³	424	420	440	435	408
Tear index, mN•m²/g	9.0	8.9	8.3	8.6	8.3
Tensile index, N•m/g	50	49	47	44	43
Scattering coef., m²/kg	64.5	60.0	63.0	66.0	68.0

1. The tensile index (left) and the scattering coefficient (right) both increase with increasing refining intensity in the first stage of a TMP system.



do not have much effect on the specific energy per impact.

For a fixed total amount of energy and with constant refining intensity and energy in the second stage, the final pulp properties depend on the refining intensity in the first stage. An increase in this refining intensity produces a pulp of lower freeness, more fines, lower shives content, and lower tear index but of higher tensile strength and scattering coefficient. This increase is illustrated in **Fig. 1** for the tensile index and the scattering coefficient.

These properties for the final pulps are also shown plotted in Fig. 1 against the average refining intensity

V. The effect of first- and second-stage rotational speed on energy — quality relationships of final pulps

	Spruce-Balsam			*Spruce*				
	1[a]	*2*[a]	*3*	*4*	*5*	*6*	*7*	*8*[b]
First stage								
E_1, GJ/ton	2.1	2.4	4.7	3.7	3.7	3.2	2.8	2.8
Rotational speed, rpm	1800	1200	1200	1200	1200	1800	1800	1800
Consistency, %	23	25	22	21	21	22	23	23
No. of impacts, thousands	4.45	11.99	18.93	14.88	14.88	6.12	5.6	5.6
e_1, 10^{-4} GJ/ton	4.76	1.99	2.49	2.49	2.49	5.19	4.97	4.97
Second stage								
E_2, GJ/ton	3.5	4.8	2.4	3.0	3.4	2.2	2.3	1.8
Rotational speed, rpm	1200	1200	1200	1200	1200	1200	900	600
Consistency, %	18	20	20	20	20	17	20	20
No. of impacts, thousands	12.41	17.93	9.86	11.86	11.86	7.82	16.49	29.69
e_2, 10^{-4} GJ/ton	2.77	2.70	2.42	2.49	2.49	2.84	1.38	0.60
Totals								
E_{total}, GJ/ton	5.6	7.2	7.1	6.7	7.1	5.4	5.1	4.6
Total no. of impacts, thousands	16.86	29.92	28.79	26.75	26.70	13.94	22.09	35.29
e_a, 10^{-4} GJ/ton	3.34	2.42	2.49	2.49	2.49	3.91	2,34	1,28
Pulp properties								
Freeness, mL CSF	93	95	97	155	157	140	150	150
L-factor, %	55	56	51	63	61	57	58	56
Fines, % (P-100)	36	36	41	30	33	34	33	35
Shives, %	0.12	0.18	~0	0.19	0.17	0.05	0.02	0.09
Density, kg/m^3	408	435	460	393	406	408	432	411
Tear index, mN•m^2/g	8.3	8.6	8.1	11	11	9.0	9.1	9.3
Tensile index, N•m/g	43	44	44	49	51	47	46	43
Scattering coef., m^2/kg	68.0	66.0	63.2	64.6	62.1	71.2	69.0	68.5

[a]From Table IV. [b]Interpolated values.

over both stages for a total specific energy of 7.1 GJ/ton. Excellent linear correlations are then obtained. Similar plots can be constructed for other pulp properties using the data from Table III. Figure 1 shows that the tensile index and the scattering coefficient are improved with increasing refining intensity in the first stage for the same total energy input.

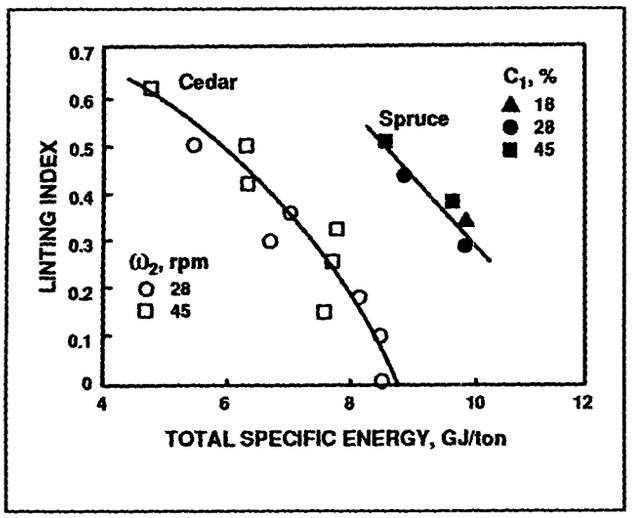
The changes in pulp properties are in the same direction as those produced by an increase in total specific energy. This suggests that the same quality of pulp can be obtained for less energy by increasing the refining intensity in the first stage. Table IV shows a selection of pulps of roughly equivalent quality in terms of L-factor, fines content, shives content, and sheet density. When the refining intensity in the first stage is increased from 0.61×10^{-4} GJ/ton to 4.8×10^{-4} GJ/ton by increasing the refiner speed from 600 rpm to 1800 rpm, the total refining energy decreases from 8.0 GJ/ton to 5.6 GJ/ton, a drop of 42%. This decrease is accompanied by a 14% drop in tensile strength, a 5% increase in scattering coefficient, and a 7% drop in tear strength. When the refiner speed is increased over the more limited range available in commercial practice, that is, from 1200 rpm to 1800 rpm, the refining intensity increases from 2.0×10^{-4} GJ/ton to 4.8×10^{-4} GJ/ton. This change brings about a reduction in the refining energy from 6.5 GJ/ton to 5.6 GJ/ton, a decrease of 14%.

These results obtained on a mixture of spruce and balsam fir are supported by data obtained on pure black spruce. These data are presented in **Table V**. The same trends are apparent when Samples 4 and 5 are compared with Sample 6. Samples 2 and 3 show that when the total energy and the total number of impacts are the same, so that the average refining intensity is the same, the pulp properties are independent of the energy split between the stages.

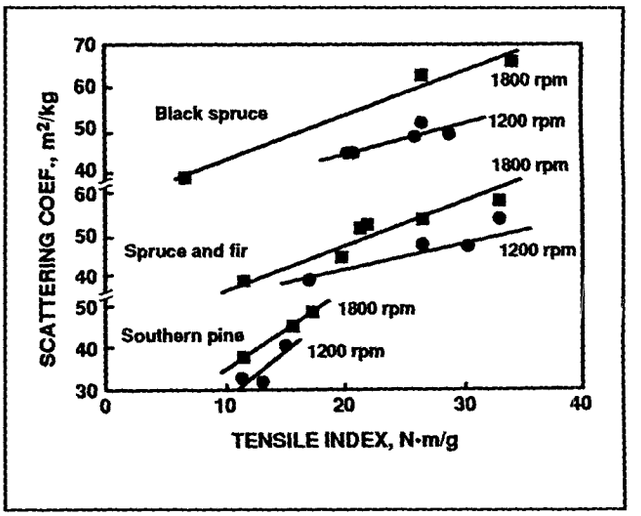
Reducing the refiner speed in the second stage from 1200 rpm to 600 rpm decreased the refining intensity from 2.84 to 0.60×10^{-4} GJ/ton. This decrease is shown in Columns 6-8 (Samples 6-8). The reduced refining intensity has brought about a decrease in the total specific energy from 5.4 GJ/ton to 4.6 GJ/ton for essentially the same pulp properties. This outcome is the opposite of what was found in the first-stage experiments. Because the speed in the first stage was 1800 rpm, the limited data available suggest that the best energy reduction might be obtained by increasing the refining intensity in the first stage and decreasing it in the second.

These results show that pulp properties such as tensile strength, shives content, and fiber length depend both on the total specific energy and on the refining intensity. Results from other experiments on cedar and black spruce show that the pulp linting propensity index (PLPI) depends solely on the specific energy. The PLPI indicates the potential of pulp fibers to lint during offset printing, and it is determined by means of the Domlar KW specific surface fractionator (*6,7*). The higher the PLPI value, the higher the tendency of pulp to produce a paper of higher linting. In

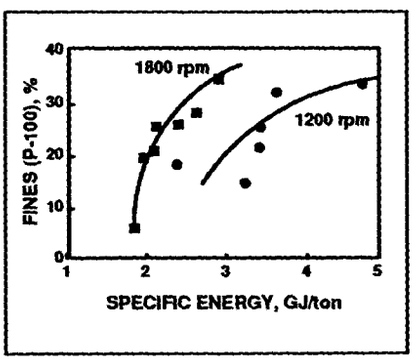
2. The pulp linting propensity index appears to depend only on the total specific energy. (C_1 denotes the discharge consistency in the first stage.)



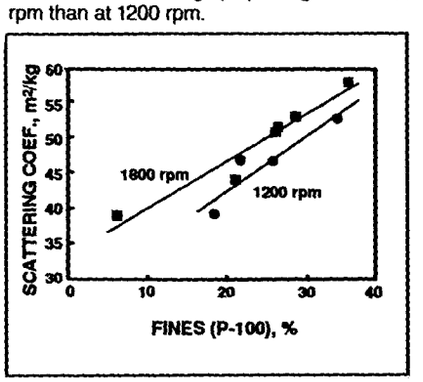
3. At a given tensile index, the scattering coefficient of the first-stage pulps was higher at 1800 rpm than at 1200 rpm. (Specific energy ranges in GJ/ton: 3.3–3.7 for black spruce, 1.8–4.7 for black spruce and fir, 3.0–4.7 for Southern pine.)



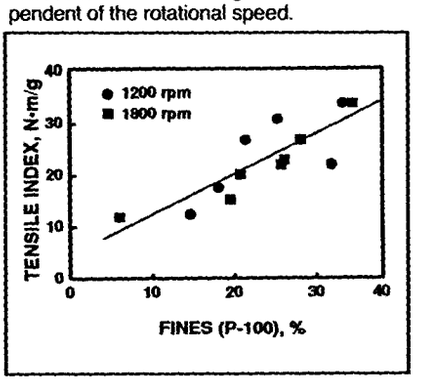
4. The fines content (P-100) of first stage pulp is higher at 1800 rpm than at 1200 rpm.



5. At a given fines content, the scattering coefficient of first stage pulp is higher at 1800 rpm than at 1200 rpm.



6. The tensile index of first-stage pulps increases with increasing fines but is independent of the rotational speed.



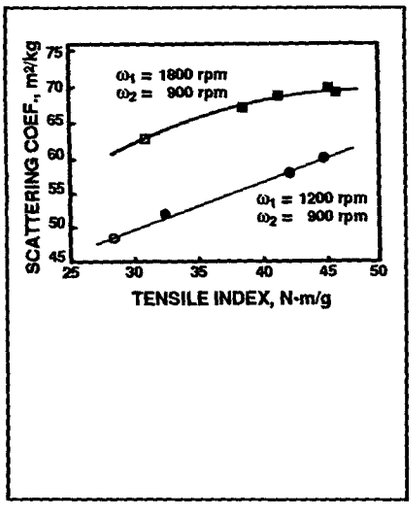
the experiments with cedar, the refining intensity was changed by running the second-stage refiner at 1200 rpm and 1800 rpm (*3*); for black spruce, the refining intensity was changed by varying the discharge consistency from 18% to 45%. The results are shown in **Fig. 2**, where the linting index is plotted against specific energy. The points of different refining intensity fall on a single curve in each case. A given value of linting index cannot be attained therefore by adjusting the refining intensity to compensate for a reduction in specific energy. Consequently, no energy reduction is possible for either species without increasing the pulp linting propensity. A possible explanation is that while the refining intensity controls the fiber length distribution for a given specific energy, it has no effect on the amount of fibers with low specific surface area, which apparently depends only on the total specific energy.

Strength and optical properties. When the scattering coefficient is plotted against tensile index for all three species used in the experiments, the scattering coefficient for a given tensile strength increases when the speed of the first-stage refiner is increased (**Fig. 3**).

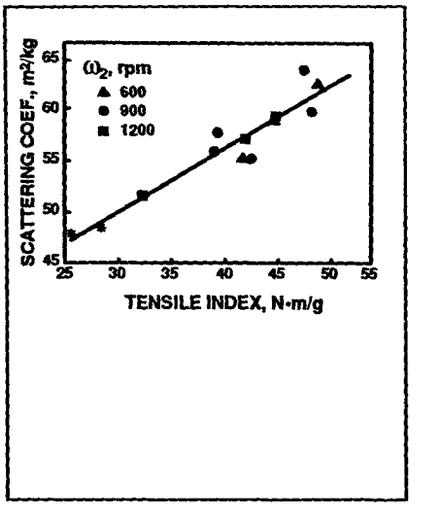
The scattering coefficient of mechanical and chemimechanical pulps depends on fiber length distribution, the quality of the long fiber fraction, and the quantity and quality of fines (*8, 9*). A plot of the fines content against specific energy shows that the fines content increases with the refiner speed (**Fig. 4**). The higher quantity of fines produced does not seem to account completely for the increase in the scattering coefficient. **Figure 5** shows that for a given fines content, the scattering coefficient is higher at 1800 rpm than at 1200 rpm. This difference could be due to a different quality of fines material. When the tensile strength is plotted against the fines content, the data for both refiner speeds fall on the same curve (**Fig. 6**). This discrepancy suggests that the various types of fines contribute differently to scattering than to bonding, which is a consideration that warrants further study.

When the tensile index of the final pulp is plotted against the scattering coefficient, as in **Fig. 7**, separate curves are obtained for the different values of first-stage refiner speed. These curves indicate that the improvement in scattering coefficient obtained by increasing the speed in the first stage is carried through the second stage of refining.

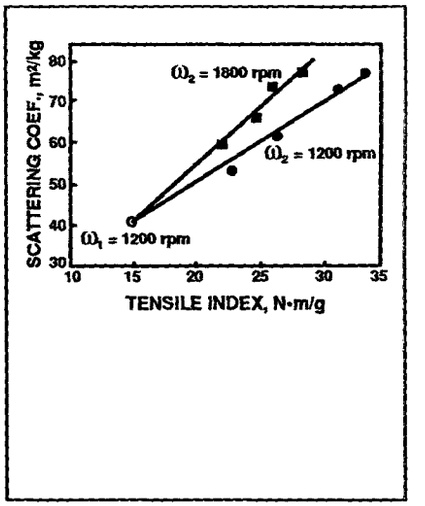
7. The increased scattering coefficient of first-stage pulps at a given tensile index obtained by increasing the speed of rotation is carried through to the second stage.



8. Increasing the second-stage refiner speed from 600 rpm to 1200 rpm has no effect on the tensile index-scattering coefficient relationship for black spruce.



9. Increasing the second-stage refiner speed from 1200 rpm to 1800 rpm increases the scattering coefficient at a given tensile index for Southern pine pulps.



An increase in the rotational speed in the second stage also increases the amount of fines (*3*). Could these be different types of fines? **Figure 8** shows a plot of scattering coefficient against tensile index for black spruce chips refined in the second stage at 600 rpm, 900 rpm, and 1200 rpm. Unlike the data for the first stage shown in Fig. 3, all points fall on the same line, indicating that the same types of fines are produced over this range of speed. The results for Southern pine when the second-stage refiner was operated at 1200 rpm and 1800 rpm are plotted in **Fig. 9**. A different line is obtained for each speed, indicating that the type of fines may be different. It is not clear whether the different performance found with Southern pine is due to the higher range of rotational speed used or to the change of species.

The effect of consistency

The pulp flow equations show that varying the rotational speed of a refiner can bring about a major change in the refining intensity. This method is not usually available to the refiner operator because the rotational speed of commercial equipment is rarely adjustable. The alternative method of varying the refining consistency is easily achieved. The effect on the final pulp properties of changing the intensity in this way was explored at the Institute's pilot plant in Kenogami, Que.

Experimental procedures

Black spruce chips were refined at 345 kPa in the 914-mm Sprout-Bauer 36-1CP first-stage refiner at a fixed rotational speed of 1800 rpm and a specific energy of 4.3 GJ/ton. Three levels of refining intensity were achieved by operating at inlet consistencies of 12.5%, 17.5%, and 22.5%. The second-stage atmospheric refining was carried out in the 914-mm Bauer 400 refiner at Pointe Claire. In this case, the inlet consistency was maintained constant at 17%, and five additional energy levels of 1.0, 2.5, 3.5, 4.5, and 5.5 GJ/ton were applied. The plates used in the first stage were Sprout-Bauer Pattern D14C001, which have a fine bar section at the outer periphery, while those used in the second stage were Pattern 36104.

Results

The number of impacts, the refining intensity, and the specific refining power in the first stage were calculated from the pulp flow equations. The results are shown in **Table VI**. The 44% decrease in consistency reduced the residence time from 0.74 s to 0.37 s. This decreased the number of impacts from 16,700 to 8100. As a result, the specific energy per impact increased from 2.6×10^{-4} GJ/ton to 5.3×10^{-4} GJ/ton, and the specific refining power increased from 5.8 GJ/ton per s to 11.5 GJ/ton per s.

These changes are substantial. The change in the refining intensity is comparable to that of changing the refiner speed from 1200 rpm to 1800 rpm (Table IV), while the change in the specific refining power is about half as much.

The effect on the total number of impacts in both stages and on the overall average refining intensity is shown in **Table VII** for the highest total specific energy used—i.e., 9.8 GJ/ton. The total number of impacts decreased by 19%, leading to a 30% increase in the average specific energy per impact and a 20% increase in the overall specific refining power. Comparison with Table IV shows that the effect on both parameters is somewhat smaller than that of changing the speed from 1200 rpm to 1800 rpm.

Properties of the first-stage pulps

The properties of the first-stage pulps are given in Table VI. They show that the increase in refining intensity at constant specific energy has brought about a decrease in the freeness and an increase in scattering coefficient. While there is little correlation between the refining intensity and the tensile index, density, and shives content, the implication remains that the energy needed to produce pulps of the same freeness and scattering coefficient from the first stage has been reduced.

Overall energy-quality relationships

Typical properties of the final pulps are shown in Table VII for a total specific energy of 9.8 GJ/ton. **Figure**

10 shows the effect of the increased average refining intensity on the freeness, tensile index, and scattering coefficient over the complete range of energy added in the second stage. For clarity in these plots, we have omitted the results obtained at the intermediate level of consistency. Interestingly, while the reduction in freeness and the increase in breaking length achieved by increasing the first-stage refining intensity continued to grow with increasing energy applied in the second stage, the increase in scattering coefficient seems to have been set in the first stage and to have remained constant thereafter.

Figure 11 shows that excellent correlation was obtained between the average specific energy per impact and the freeness, tensile index, and scattering coefficient of the final pulp at a constant total specific energy. The same degree of correlation was obtained with the overall specific refining power. The scattering coefficient is plotted against tensile index in **Fig. 12** for the three levels of consistency used in the first stage. The scattering coefficient at a given tensile index is independent of the refining intensity in the first stage. This result is different from that obtained when refining intensity was changed by changing the speed, as shown in Fig. 3. (This difference will be discussed shortly.)

Table VIII shows the results of interpolating the final pulp properties to equal values of freeness (190 mL CSF), tensile index (41 N·m/g), and scattering coefficient (56.5 m^2/kg). The total specific energy needed to achieve this quality of pulp has decreased from 9.7 GJ/ton to 8.6 GJ/ton—that is, by 11%.

VI. The effect of consistency on properties of first-stage pulps (black spruce)

Refining			
E_1, GJ/ton	4.3	4.3	4.3
Inlet consistency, %	22.5	17.5	12.5
Residence time, s	5.28	2.63	1.45
Total no. of impacts, thousands	57.65	41.12	26.25
e_1, 10^{-4} GJ/ton	2.6	3.6	5.3
$\dot{e}_1$, GJ/ton per s	5.8	7.9	11.5
$\dot{e}_1/e_1$, s^{-1}	2.23	2.19	2.17
Pulp properties			
Freeness, mL CSF	633	592	583
Shives, %	3.42	2.62	3.10
Density, kg/m^3	207	214	211
Tear index, mN·m^2/g	4.97	5.3	5.02
Tensile index, N·m/g	14.6	17.2	16.4
Scattering coef., m^2/kg	42.3	44.1	45.1

VII. The effect of first-stage consistency on properties of second-stage pulps (black spruce)

Refining			
E_1, GJ/ton	9.8	9.8	9.8
Inlet consistency, %	22.5	17.5	12.5
Residence time, s	1.98	1.84	1.67
Total no. of impacts, thousands	39.8	36.3	32.4
e_a, 10^{-4} GJ/ton	2.4	2.7	3.1
$\dot{e}_a$, GJ/ton per s	4.9	5.4	5.9
Pulp properties			
Freeness, mL CSF	179	154	113
Density, kg/m^3	375	369	390
Tear index, mN·m^2/g	9.98	10.32	9.44
Tensile index, N·m/g	42.6	45.5	48.4
Scattering coef., m^2/kg	56.7	58.6	60.5

Discussion

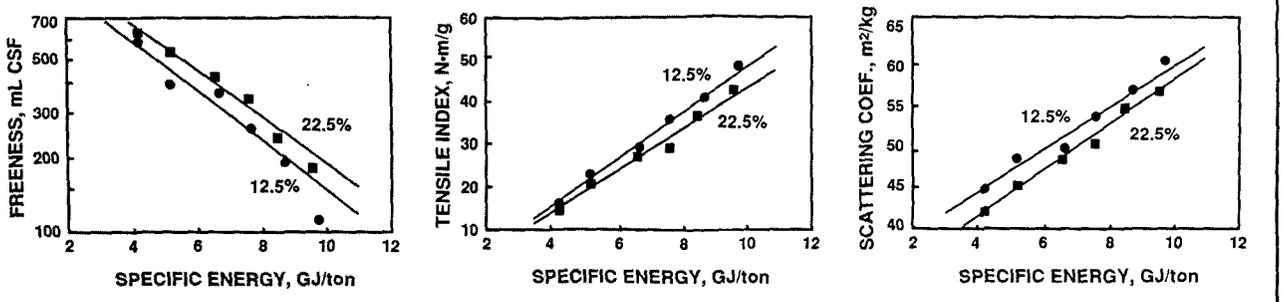
The analysis of the data obtained with the three different species used in the experiments indicates that benefits in either pulp quality or energy consumption can be obtained when the first-stage refining is carried out at high refining intensity. The effect is obtained when the refining intensity is increased either by increasing the rotational speed or by decreasing the consistency.

When the increase is obtained by increasing the refiner speed, the refining intensity increases rapidly because of its sensitivity to the speed. The specific energy in the first stage must then be kept low, at less than 2 GJ/ton, or irreparable damage will be done to the fiber length. This is seen from comparing Samples 4 and 5 with Samples 6-8 in Table V. In the case of Samples 6-8, the specific energy per impact has become too high, 5.0 × 10^{-4} GJ/ton and the onset of a loss of fiber length and tear is apparent. The finding from these experiments that high refining intensity leads to more "effective" refining in mechanical pulping, apart from the reduction of fiber length, has also been demonstrated in experiments with single-stage RMP (*2*). The importance of the initial wood defibration process has also been demonstrated recently in pulp grinding experiments (*10*).

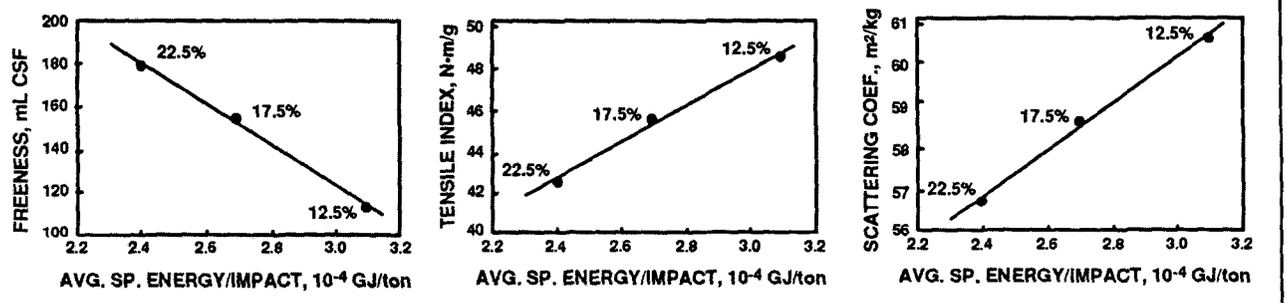
Decreasing the consistency in the first stage produces a less rapid increase in the refining intensity than that produced by an increase in speed. More specific energy then has to be applied to produce similar benefits on pulp quality and energy reduction.

As mentioned, increasing the speed produces a change in the scattering coefficient for a given tensile strength, and it has been suggested that this might be due to a change in the type of fines produced. Changing the consistency does not produce a similar effect. There is an important difference between the two ways of controlling the refining intensity that follows directly from the pulp flow equations. When the consistency is decreased, both the refining intensity, e, and the specific refining power, $\dot{e}$, change at the same rate, so the ratio $\dot{e}/e$ remains the same. This is shown in Table VI.

10. At a constant total specific energy, as the consistency in the first stage is decreased, the final pulp freeness decreases, the tensile index increases, and the scattering coefficient increases. (Inlet consistencies of 12.5% and 22.5%.)



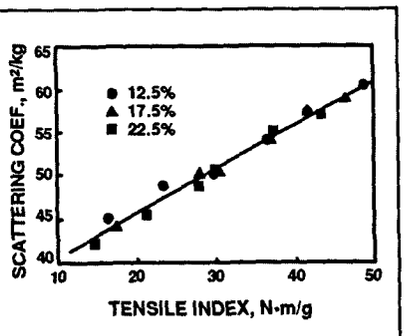
11. The freeness decreases, whereas tensile index, and scattering coefficient of the final pulp at a constant total specific energy increase in direct proportion to the overall refining intensity. (Inlet consistencies of 12.5%, 17.5%, and 22.5%.)



VIII. Energy required to achieve the same pulp quality at different refining intensities (black spruce)

Refining			
1st-stage consistency, %	22.5	17.5	12.5
E_1, GJ/ton	4.3	4.3	4.3
E_2, GJ/ton	5.4	4.6	4.3
E_{total}, GJ/ton	9.7	8.9	8.6
Total no. of impacts, thousands	39.8	30.9	25.8
e_a, 10^{-4} GJ/ton	2.4	2.9	3.3
Pulp properties			
Freeness, mL CSF	190	190	190
Shives, %	0.11	0.20	0.24
Density, kg/m³	371	352	355
Tear index, mN•m²/g	10.0	10.3	9.7
Tensile index, N•m/g	41.5	41.5	41.0
Scattering coef., m²/kg	56.5	56.7	56.5

12. Increasing the refining intensity in the first stage by decreasing the inlet consistency has no effect on the relationship between tensile index and scattering coefficient for the final pulp.



When the speed is increased, $\dot{e}$ changes more rapidly than e, so that the ratio increases. This may be an explanation for the different effects on the pulp quality interrelationships. The effect will be studied further.

A high specific energy per impact can also be achieved by changing the plate pattern to reduce the number of impacts for a given total specific energy; this has not yet been explored systematically. The specific energy per impact must again be set below the level at which it will cause serious damage to the fibers.

Carrying out second-stage refining at lower specific energy per impact seems to be effective in producing a decrease in the overall energy consumption for a given pulp quality. This result was achieved in the experiment by refining at low rotational speed. Presumably the same effect could be achieved by refining at higher consistency or by using finer plate patterns.

The benefits expected from the type of optimization explored here are either better strength and optical properties or alternatively, energy savings for the same properties. The choice is governed by the specifications of quality needed to produce the desired grade of paper.

These results are preliminary, and more data are needed. The approach will be extended to the optimization of the strength and opacity relationships in chemimechanical pulps. More research is needed to determine the effects of combining high and low refining intensity on the fiber morphology, from which the changes in the pulp properties and energy consumption arise.

Conclusions

Changing the refining intensity in the first stage of a conventional two-stage thermomechanical refining system changes the energy-quality relationships in the final pulp. The refining intensity can be adjusted either by changing the speed of the refiner or the consistency.

A higher refining intensity in the first stage produces pulps with better strength and optical properties for the same consumption of energy. The pulps have higher scattering coefficient at equivalent strength.

The refining intensity does not affect the linting propensity, which appears to depend solely on the total applied energy.

Finally, there are indications that the beneficial effects of a high refining intensity in the first stage are enhanced if this stage is followed by a low refining intensity in the second stage.□

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