

Kraft pulping of second-growth lodgepole pine

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ABSTRACT: *The yield and quality of 36 unbleached kraft pulps from 12 second-growth lodgepole pine trees at four sites in British Columbia and Alberta have been determined. Tree samples were separated into butt juvenile wood, butt mature wood, and top wood components for kraft pulping, pulp property, and handsheet evaluation.*

Relative to mature wood, juvenile wood samples provided bleachable-grade pulps with lower yield and slightly decreased alkali consumption, but with similar H factors. Kraft pulp fibers from juvenile wood and top wood samples were finer and shorter than their mature wood counterparts and gave denser sheets that were smoother and less porous. Tensile and burst indexes and stress-strain factors were higher, too, so these finer-fibered pulps would be more preferable for many paper grades such as lightweight coated.

KEYWORDS: *Canada, chemical pulping, density, fibers, juvenile wood, kraft pulping, kraft pulps, mature wood, mechanical properties, physical properties, pinus contorta, pulp properties, secondary forest, statistical analysis, unbleached pulps, yield.*

Managed forests grow faster than old-growth stands and will be harvested sooner, leading to a marked increase in juvenile or core wood in trees of the twenty-first century. In Canada, young trees (<20 years old) contain up to 100% juve-

nile wood, in contrast to 60-year-old and 150-year-old trees, which typically contain 50% and 15% juvenile wood, respectively (Fig. 1). Since the ratio of sawmill residual to woodroom chips used in Canadian pulping is about 3:2 (1), it follows

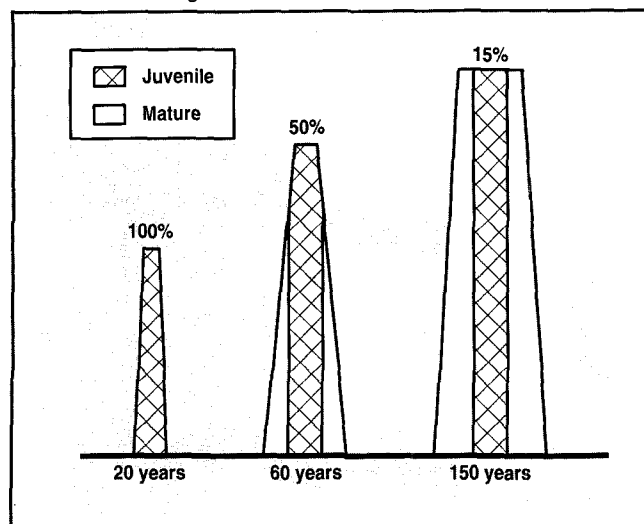
that more than 90% of the chips used for pulp production presently originate from mature wood. Thus, although the physical and chemical properties of juvenile wood differ from those of presently-used mature wood, the impact to date on Canadian industry has been relatively minor. The resource is, however, undergoing constant change (2), and the industry needs information now on how this will impact processing and management practices. Accordingly, the central objective in our continuing studies on second-growth Canadian softwoods has been to determine the wood chemistry, and the processing characteristics and properties of kraft and mechanical pulps. Our earlier work has described the wood chemistry (3, 4) and the kraft pulping (5-7) of second-growth Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] from British Columbia and jack pine (*Pinus banksiana* Lamb.) from eastern Canada. More recently, the wood chemistry of second-growth lodgepole pine (*Pinus contorta* Dougl.) from British Columbia and Alberta was reported (8).

With the exception of one paper on the complete-tree utilization of western hemlock (9), there are no published data on the kraft pulping of juvenile and mature wood from second-growth western Canadian softwoods.

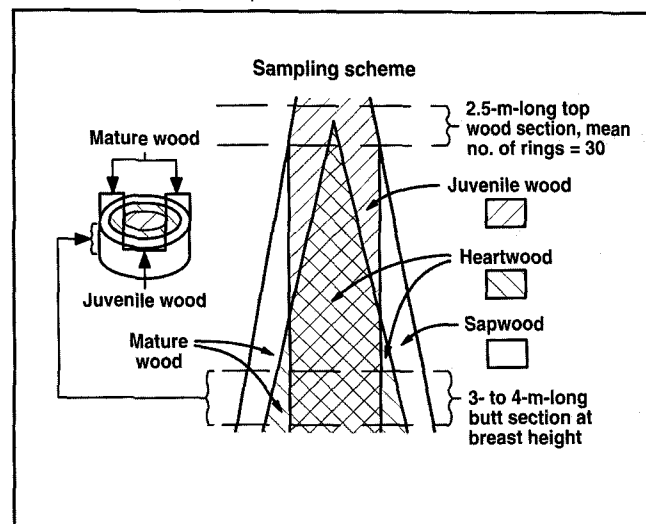
Lodgepole pine, considered a weed species in the 1950s, is now highly regarded in British Columbia, Alberta, and the western United

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1. Typical contents of juvenile wood in Canadian softwoods at different rotation ages



2. Schematic showing the sampling scheme for butt juvenile wood, butt mature wood, and top wood from each of the 12 trees



States for the production of chemical and mechanical pulps (10), yet literature data on the kraft pulping of lodgepole pine are relatively sparse. Early papers cite the suitability of lodgepole pine as a furnish for kraft pulps (11, 12). The strength of pilot-scale kraft pulps has been compared with that of other Canadian softwood kraft pulps (13). Pulp yield of lodgepole pine was found to increase by 0.40% for a unit increase in permanganate number (14). The efficacy of using barky (15) and forest residual (16) lodgepole pine chips in kraft pulping has been demonstrated. Detailed studies on the pulp yield and other losses to be expected in the outside storage of lodgepole pine chips have been reported (17, 18) as has the effect of Atropellis canker on the growth and use of lodgepole pine (19). Forest yield can be increased by either pulping tops (20) or by using trees salvaged from reservoirs built to generate hydroelectric power (21). There are, however, no data on the kraft pulping of juvenile and mature wood from second-growth lodgepole pine trees.

The first report in this series presented data on the wood properties of lodgepole pine from two sites in British Columbia and two sites in Alberta (8). This paper presents corresponding data on the pulping

I. Locations of lodgepole pine sites

Site	Latitude	Longitude
Loon Lake, BC	51°03'N	116°48'W
Sulphur Springs, BC	50°01'N	114°52'W
Simonette, AB	54°19'N	117°59'W
Marlboro, AB	53°38'N	116°55'W

characteristics, yields, and physical properties of unbleached kraft pulps made from the same samples used previously.

Materials and methods

Site and stand characteristics

Second-growth lodgepole pine was chosen from two sites in British Columbia and two sites in Alberta located as shown in Table I.

Tree selection

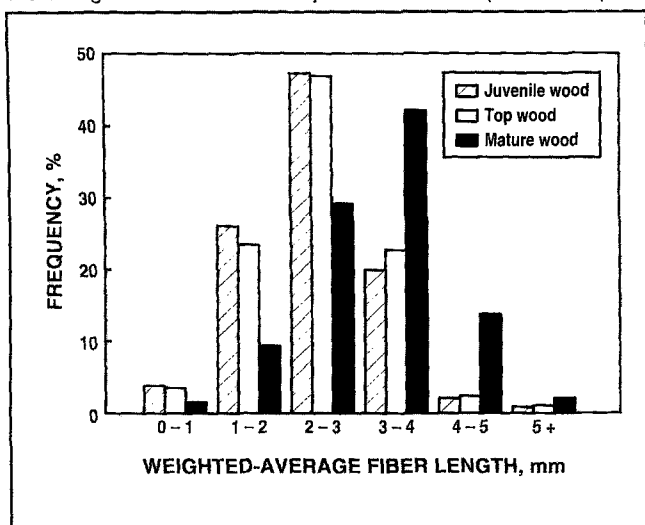
Three trees were selected from each site, one each of low, medium, and high density, based on field determination of wood density using breast height (BH) increment cores (3). A large range of wood density was sought to derive meaningful relationships between wood and pulp properties.

Sample procurement

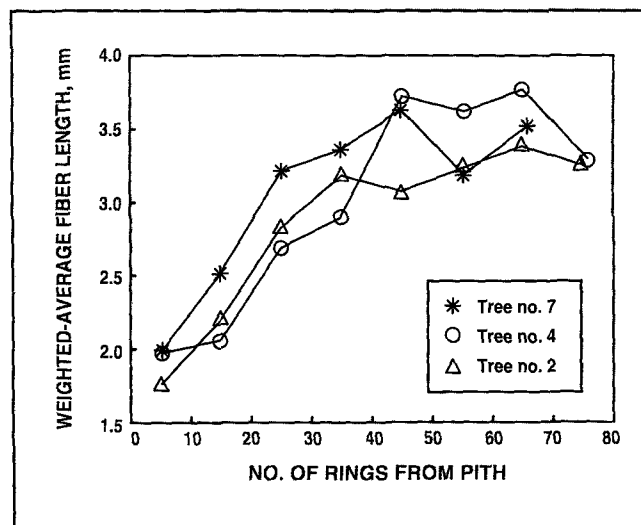
Juvenile wood was defined as the innermost region of 25 annual rings, the inner cylinder of wood that surrounds the pith from the base to the top of the stemwood. Three samples were taken from each tree, juvenile and mature wood from the butt and top wood, according to the schematic shown in Fig. 2. After felling, the butt end of each tree was trimmed, and the radius of the inner 25 rings was measured.

The volume of juvenile wood was established for a 1-m-long bolt at breast height. To provide sufficient wood for pulping, about three more 1-m-long bolts were taken above the first and adjacent to it. In addition to the butt bolts, two adjacent 1.25-m-long bolts were removed from a position about 80% up the total height of each stem, at which the annual rings varied from 20 to 40. These

3. Bleachable-grade kraft pulps from mature wood samples contain more long fibers than those from juvenile wood or top wood samples.



4. Weighted-average fiber length of kraft pulps from butt sections of three trees from Loon Lake



samples were mostly juvenile wood and served as an internal check on the juvenile wood from the breast height bolts, which were all heartwood. Top wood samples represent, but are not identical to, material typical of thinnings of a similar age. The bolts were transported within three days to the Vancouver laboratory and stored frozen until processed.

Chip preparation

After thawing the samples obtained from Loon Lake and Sulphur Springs, British Columbia, and Simonette and Marlboro, Alberta (8), butt and top wood bolts were debarked, and butt bolts were slabbed on a band saw to produce juvenile wood and mature wood sections (Fig. 2). These sections of juvenile wood, mature wood, and top wood were chipped in a CAE six-knife disc chipper to provide chips for mechanical and kraft pulping trials. Each of the 36 chip samples (4 sites x 3 trees x 3 components) was screened to remove oversize and fine material, and each was well mixed before representative samples were taken.

Kraft pulping

Three series of kraft cooks were made.

First series. Three representative aliquots of accept chips from each of the 36 samples available were cooked in bombs [50 g oven-dry (o.d.) charges] within a precision digester assembly (22) to produce bleachable-grade kraft pulps with kappa numbers from 25 to 55. This is equivalent to a Klason lignin range of 3.75% to 8.25% o.d. pulp basis. It is much narrower than the 4–19% ranges used for second-growth Douglas-fir (5) and jack pine (7), which included linerboard grade lignin levels of 15%. Accept chips were those that passed 28.5-mm holes on a shaker screen but were retained in 5-mm holes; all accept chips were further screened through slots to accept those from 2 mm to 6 mm thick.

The following kraft cooking conditions were used:

- Time to maximum temperature: 135 min
- Maximum cooking temperature: 170°C
- H factor: 820 to 1520
- Effective alkali (EA): 16.0% o.d. wood
- Sulfidity: 25.0%
- Liquor-to-wood ratio: 4.5:1.

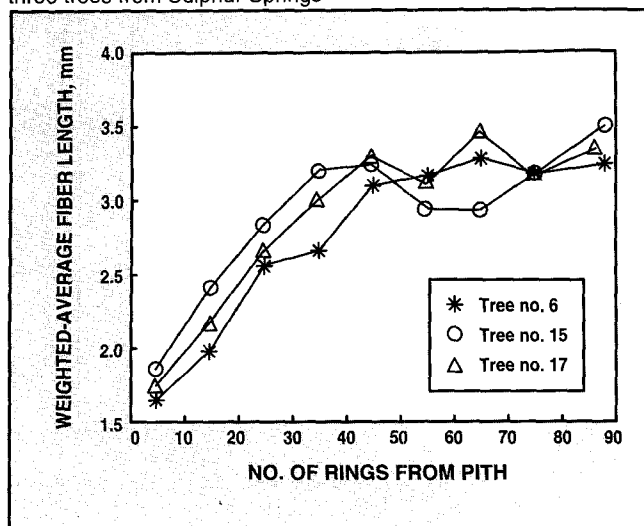
Each pulp was washed and processed according to standard proce-

dures developed in our laboratory. The residual effective alkali (EA_{res}) of each black liquor was determined by barium carbonate precipitation and potentiometric titration with hydrochloric acid to pH 8.3, as recommended by Kesler (23). Thus, 36 x 3, or 108, measurements of each of pulp yield, H factor, and EA_{res} were made. For all 36 samples, regression lines were fitted through each three-cook set to give 108 regression equations (with r^2 0.97) from which pulp yield, H factor, and effective alkali consumed were estimated at kappa no. 35 ($\approx$ 5.25% Klason lignin o.d. pulp), representative of bleachable-grade pulps.

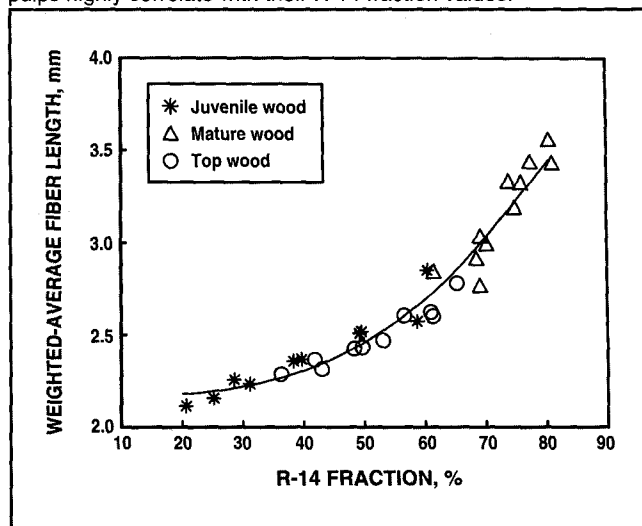
Second series. To produce large quantities of unbleached kraft pulps with kappa numbers of approximately 35, 36 more samples, each of 3.5-kg o.d. wood, were individually cooked in a 28-L Weverk laboratory digester. Cooking conditions were based on data produced in the first series of cooks. All pulps were washed, screened, and processed as stated above.

Third series. A new technique was developed for the purpose of cooking a large number of 5-g o.d. wood samples to kappa numbers from 15 to 40 (24). More than 200 individual samples taken from the Loon Lake

5. Weighted-average fiber length of kraft pulps from butt sections of three trees from Sulphur Springs



7. Weighted-average fiber lengths of all 36 bleachable-grade kraft pulps highly correlate with their R-14 fraction values.



and Sulphur Springs test trees at different locations along each stem from base to crown, and from pith to bark, were cooked by the kraft process to provide samples for analysis of fiber length.

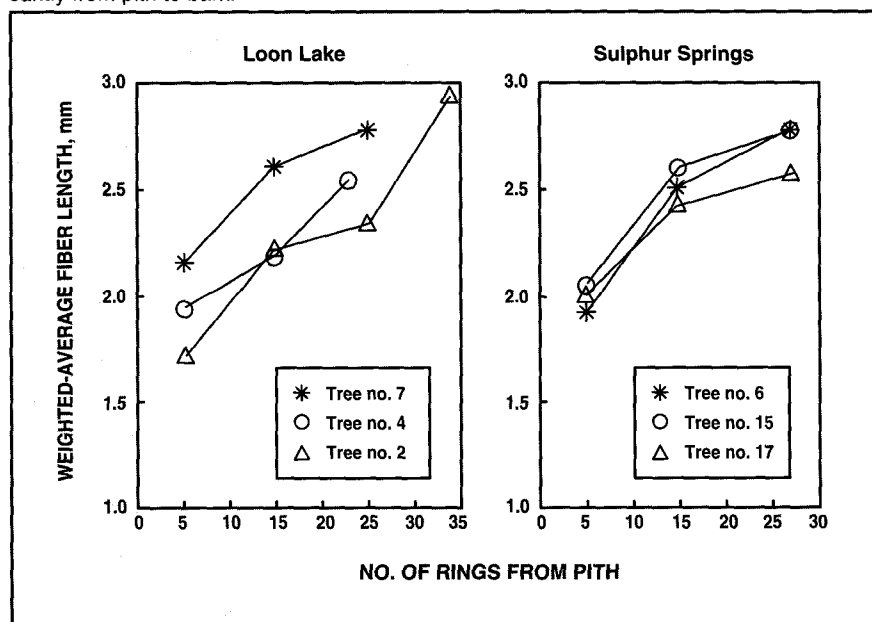
Fiber properties

Representative samples of more than 10,000 fibers from each of the 36 large-scale bleachable-grade kraft cooks (second series) were analyzed for fiber length and coarseness using a Kajaani FS-200 instrument. The 200-plus miniature kraft pulp samples were similarly analyzed for fiber length, and appropriate data were used to plot fiber length distributions from pith to bark for butt and top wood sections of the six British Columbia trees sampled.

Handsheet properties

Five representative samples of each kraft pulp (second series) were beaten in a PFI mill for 0, 1000, 3000, 6000, and 12,000 revolutions. Handsheets were made and tested for bulk, mechanical, and optical properties using standard methods to give 36 x 5, or 180, sets of data for analysis.

6. Weighted-average fiber lengths of kraft pulps from top wood samples increase significantly from pith to bark.



Results and discussion

Kraft cooking of juvenile wood, mature wood, and top wood components

Pulp yields at kappa no. 35 (bleachable-grade) for all juvenile wood, mature wood, and top wood components estimated from data obtained in the first series of cooks are shown in Table II, together with their

corresponding H factors and effective alkali consumptions.

For each tree, yields from juvenile wood were always lower than those from their corresponding mature wood component. Differences ranged from a low of 0.4 to a high of 5.4%, with a mean and standard deviation (S.D.) of 2.5 and 1.5% o.d. wood, respectively. This mean value is similar to the 2.7% observed for second-growth jack pine (?); both

II. Kraft cooking of second-growth lodgepole pine to kappa no. 35

<i>Tree no.</i>	<i>Wood sample</i>	<i>Chip density, kg/m³</i>	<i>Pulp yield, % o.d. wood</i>	<i>Hfactor</i>	<i>Effective alkali consumed, % o.d. wood</i>
Loon Lake, BC					
7	JW ^a	385	46.2	1170	10.5
	MW ^b	450	46.6	1300	11.0
	TW ^c	435	46.1	1325	11.0
4	JW	375	44.3	1200	10.5
	MW	420	49.7	1150	10.5
	TW	390	46.9	1270	11.0
2	JW	370	47.7	1150	10.4
	MW	405	48.5	1200	10.6
	TW	370	47.7	1220	10.8
Sulphur Springs, BC					
6	JW	380	45.8	1180	10.3
	MW	405	48.9	1180	10.4
	TW	390	47.6	1240	10.8
15	JW	370	45.2	1230	10.7
	MW	405	47.9	1225	10.6
	TW	390	46.0	1360	11.1
17	JW	345	43.6	1200	10.6
	MW	370	48.2	1180	10.5
	TW	380	46.6	1270	11.0
Simonette, AB					
8	JW	395	44.6	1170	10.6
	MW	415	46.7	1210	10.8
	TW	385	46.5	1260	11.0
7	JW	365	44.2	1190	10.5
	MW	375	47.0	1180	10.7
	TW	385	46.9	1290	10.9
5	JW	325	45.5	1185	10.9
	MW	355	46.4	1270	10.9
	TW	350	47.3	1280	10.8
Marlboro, AB					
7	JW	370	43.6	1160	10.6
	MW	395	46.1	1170	10.9
	TW	400	47.1	1280	10.7
3	JW	340	44.9	1190	10.6
	MW	375	47.7	1180	10.6
	TW	390	47.7	1165	10.6
10	JW	340	44.8	1195	10.5
	MW	350	46.4	1150	10.6
	TW	345	46.2	1175	10.9

^aButt juvenile wood (first 25 annual rings)

^bButt mature wood (rings 26 - 73+)

^cTop wood (average age: 30 years)

Fiber Supply

pine values were substantially larger than the 1.6% observed for second-growth Douglas-fir (5). Yields from the top wood component of each tree generally were higher than those from the corresponding juvenile wood component. Mean and S.D. values (shown in parentheses) of pulp yield for each 12-sample composite set of juvenile wood, mature wood, and top wood components were 45.0 (1.2), 47.5 (1.2), and 46.9 (0.6)% o.d. wood, respectively, which reflects wood chemistry differences described earlier (8).

The H factors required to produce these pulps at kappa no. 35 were similar, with means and S.D. values of 1185 (21), 1200 (46), and 1260 (56) for each 12-sample composite set of juvenile wood, mature wood, and top wood, respectively. However, paired difference analysis (paired *t* test) (25) showed that the H factors for top wood pulps were significantly higher at the 5% level than either of those for juvenile wood or mature wood, which were statistically equivalent.

In contrast to the results for second-growth jack pine (7), less alkali was required to cook each juvenile wood component from a given tree compared with mature wood and top wood components, but the differences were small. Mean and S.D. values of the effective alkali consumed for each 12-sample composite set of juvenile wood, mature wood, and top wood components were 10.56 (0.15), 10.68 (0.19) and 10.88 (0.15)% o.d. wood, respectively. There was no significant difference at the 5% level between alkali requirements for juvenile wood and mature wood samples, but these were both significantly lower than the alkali consumption for top wood samples. Thus, pulp yields were lower for juvenile wood relative to mature wood components by 2.5% o.d. wood, but H factors and alkali requirements were similar.

Pulp properties

Fiber coarseness. Values of fiber coarseness for the 36 bleachable-

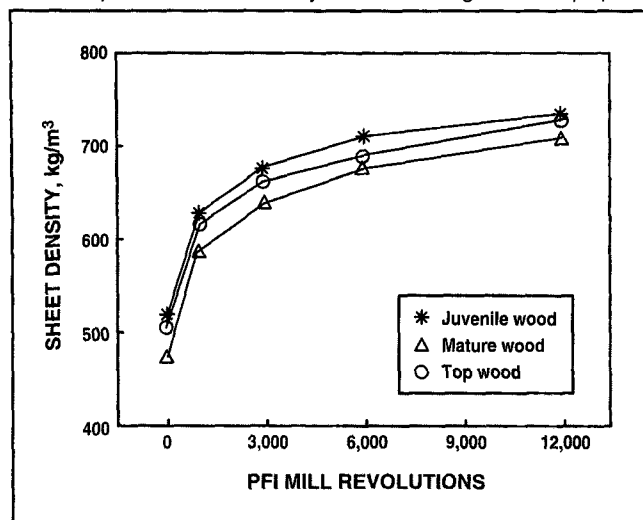
III. Pulp properties of second-growth lodgepole pine

Tree no.	Wood sample	Fiber coarseness, $\mu\text{g/m}$	Weighted-average fiber length, mm	R-14 fraction, %
Loon Lake, BC				
7	JW	225	2.84	60.0
	MW	244	3.42	77.3
	TW	179	2.77	65.1
4	JW	184	2.37	40.0
	MW	230	3.12	57.9
	TW	215	2.32	43.0
2	JW	188	2.57	58.5
	MW	238	3.30	75.8
	TW	169	2.60	61.1
Sulphur Springs, BC				
6	JW	203	2.50	49.2
	MW	281	3.53	80.2
	TW	190	2.55	75.0
15	JW	177	2.52	49.6
	MW	234	3.31	73.6
	TW	168	2.62	60.8
17	JW	172	2.49	49.4
	MW	222	3.40	80.8
	TW	160	2.46	53.0
Simonette, AB				
8	JW	183	2.51	48.7
	MW	233	3.01	69.2
	TW	183	2.42	48.5
7	JW	198	2.36	38.1
	MW	242	2.83	61.3
	TW	188	2.37	41.9
5	JW	167	2.26	28.7
	MW	203	2.98	70.2
	TW	165	2.29	36.4
Marlboro, AB				
7	JW	164	2.24	31.3
	MW	201	2.89	68.5
	TW	168	2.47	52.8
3	JW	150	2.15	25.1
	MW	214	3.17	74.8
	TW	171	2.60	56.5
10	JW	135	2.12	20.8
	MW	171	2.75	68.8
	TW	149	2.43	49.6

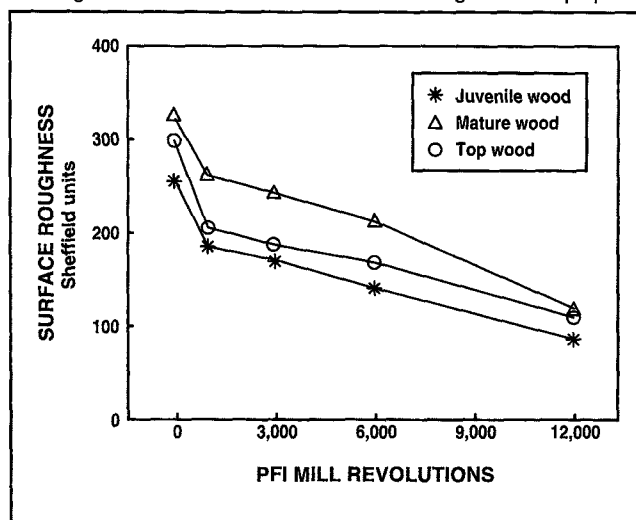
grade kraft pulps (second series of cooks) are shown in Table III. They ranged from 135 $\mu\text{g/m}$ to 281 $\mu\text{g/m}$, which is a broader range than those observed earlier for second-growth Douglas-fir (170–269 $\mu\text{g/m}$) (5) and

jack pine (171–284 $\mu\text{g/m}$) (7). For each of the 12 trees, fibers from juvenile wood and top wood kraft pulps were consistently less coarse than those from their corresponding mature wood pulps. Thus, kraft pulps

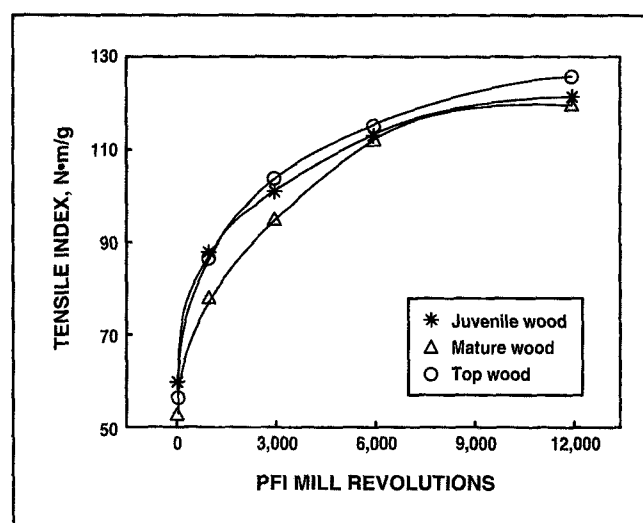
8. Development of sheet density in bleachable-grade kraft pulps



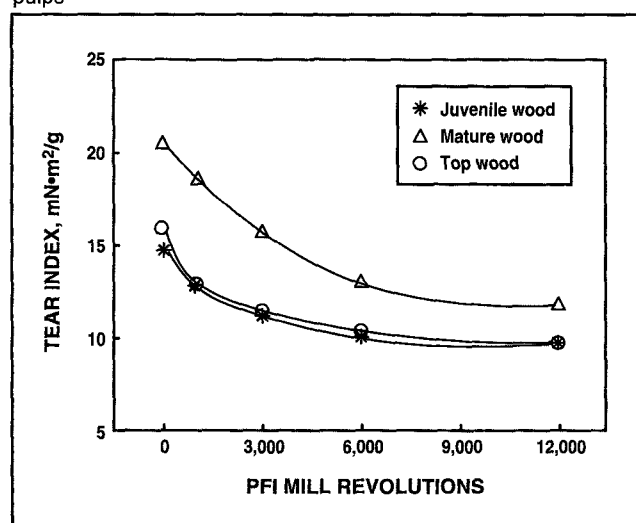
9. Roughness of handsheets from bleachable-grade kraft pulps



10. Tensile index of bleachable-grade kraft pulps



11. Tear index vs. PFI mill revolutions of bleachable-grade kraft pulps



from the juvenile wood butt section of each tree would be expected, because of their finer fibers, to show increased interfiber bonding, leading to higher burst and tensile indexes. However, we expect reduced tear indexes compared with pulps from the mature wood butt section of the same tree.

Fiber length distribution in bleachable-grade pulps. Fiber length distributions of the 36 bleachable-grade kraft pulps from the second series of cooks were grouped by tree component, as shown in Fig. 3. The proportion of long fibers in-

creased in the order of juvenile wood less than top wood less than mature wood, which is confirmed by the mass-weighted-average length (hereafter called weighted-average fiber length) values of 2.41, 2.49, and 3.14 mm for juvenile wood, top wood, and mature wood samples, respectively. The larger value for top wood relative to juvenile wood is probably due to the older age of the former (30 vs. 25 years) and the presence of mature wood fibers, which boost the weighted-average fiber length values (8).

The pith-to-bark weighted-average fiber lengths of bleachable-grade kraft pulps determined by means of the miniature kraft cooks (24) are shown in Figs. 4 and 5 for butt samples from the British Columbia locations of Loon Lake and Sulphur Springs, respectively. Corresponding data for the two Simonette and Marlboro, Alberta, locations are not available. The corresponding distributions for top samples are shown in Fig. 6. Fiber lengths increased steadily for the first 45 years before leveling off throughout the mature wood component of a tree.

IV. Selected handsheet physical properties^a of bleachable-grade kraft pulps from second-growth lodgepole pine

Property	Wood sample	PFI revolutions				
		0	1,000	3,000	6,000	12,000
CSF, mL	JW	682 (35) ^b	661 (37)	630 (41)	562 (39)	409 (40)
	MW	722 (17)	711 (21)	682 (29)	611 (27)	383 (49)
	TW	699 (22)	677 (18)	650 (19)	603 (22)	445 (43)
Sheet density, kg/m ³	JW	520 (72)	631 (49)	675 (39)	707 (34)	730 (28)
	MW	472 (79)	587 (58)	637 (44)	675 (38)	704 (32)
	TW	505 (52)	615 (35)	662 (23)	687 (18)	725 (19)
Surface roughness, Sheffield units	JW	256 (76)	188 (61)	171 (57)	140 (52)	85 (32)
	MW	326 (58)	262 (59)	243 (51)	213 (48)	115 (33)
	TW	302 (44)	207 (42)	188 (33)	168 (31)	107 (27)
Tensile index, N·m/g	JW	60 (20)	88 (16)	101 (11)	113 (9)	121 (10)
	MW	53 (23)	78 (19)	95 (16)	112 (12)	119 (10)
	TW	57 (19)	87 (14)	104 (10)	115 (9)	125 (8)
Air resistance, s/100 mL	JW	5 (7)	12 (13)	21 (21)	45 (47)	124 (77)
	MW	1 (2)	2 (4)	4 (6)	10 (11)	63 (35)
	TW	2 (3)	5 (5)	8 (8)	14 (12)	65 (32)
Stress-strain factor, mJ/g	JW	970 (600)	1750 (595)	2170 (445)	2590 (330)	2865 (335)
	MW	615 (470)	1315 (570)	1835 (540)	2370 (445)	2670 (415)
	TW	780 (425)	1525 (460)	2065 (335)	2470 (315)	2840 (205)
Zero-span breaking length, km	JW	18.3 (1.4)	19.7 (1.4)	19.8 (1.1)	20.0 (1.1)	20.0 (1.1)
	MW	19.4 (1.5)	20.7 (0.9)	20.1 (1.3)	20.2 (1.1)	20.4 (1.2)
	TW	18.3 (1.6)	20.7 (1.1)	21.2 (0.8)	20.9 (0.9)	21.2 (1.0)
Burst index, kPa·m ² /g	JW	4.3 (1.8)	6.9 (1.4)	8.3 (1.0)	9.3 (0.7)	10.0 (0.7)
	MW	3.4 (2.0)	6.4 (1.6)	7.9 (1.5)	9.4 (1.2)	10.3 (1.1)
	TW	3.8 (1.7)	6.7 (1.3)	8.5 (1.1)	9.6 (0.9)	10.5 (0.8)
Tear index, mN·m ² /g	JW	14.8 (2.7)	12.8 (2.7)	11.2 (1.9)	10.0 (1.4)	9.6 (1.2)
	MW	20.5 (4.5)	18.7 (4.9)	15.7 (4.0)	13.0 (2.5)	11.7 (1.7)
	TW	16.0 (3.8)	13.0 (1.6)	11.5 (1.0)	10.3 (0.8)	9.7 (0.8)

^a Each number is the mean of 12 samples.
^b Figures in parentheses are standard deviations; they are included only to show the spread of data observed and are not intended for use in testing for statistical significance.

As found for second-growth Douglas-fir (5) and jack pine (7), tree differences were apparent but could not be explained on a basis of chip density differences (Table II).

Weighted-average fiber length. The weighted-average fiber lengths of the bleachable-grade kraft pulps are shown in Table III. They ranged from 2.12 mm to 3.53 mm, a wider range than those earlier observed (5, 7). For each of the 12 trees, the average fiber lengths of juvenile wood kraft pulps were consistently smaller than those of their corre-

sponding mature wood pulps. These trends are consistent with the pith-to-bark fiber lengths shown in Figs. 4-6.

R-14 Bauer-McNett fraction. The fiber fractions retained on the 14-mesh screen during Bauer-McNett fractionation of the bleachable-grade kraft pulps are shown in Table III. They ranged from a low of 20.8% to a high of 80.8%. All 36 R-14 values were highly correlated with weighted-average fiber length, WAFL, (Fig. 7) by means of the quadratic equation:

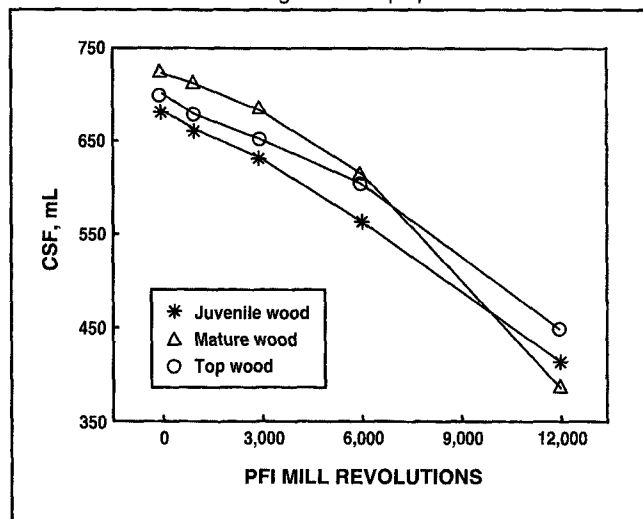
$$WAFL = 2.46 - 2.00 \times 10^{-2}(R-14) + 4.01 \times 10^{-4}(R-14)^2 \quad (1)$$

where $r^2 = 0.95$.

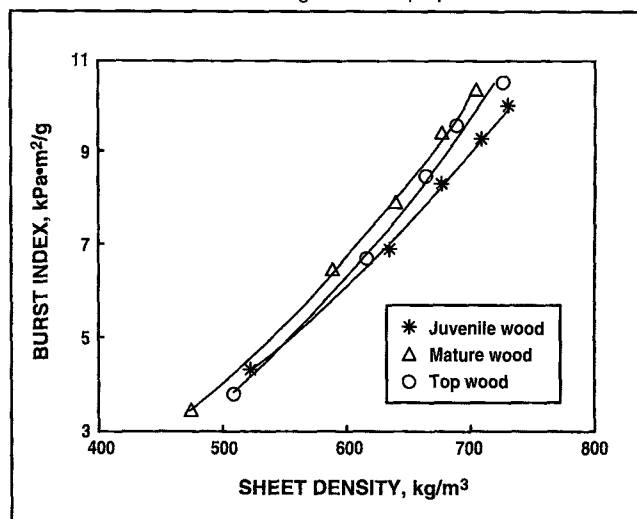
Handsheet properties of bleachable-grade kraft pulps

Handsheets from unbeaten and beaten samples of the bleachable-grade kraft pulps were tested for their bulk, mechanical, and optical properties, and the development of sheet properties was described by using a given level of beating as a baseline.

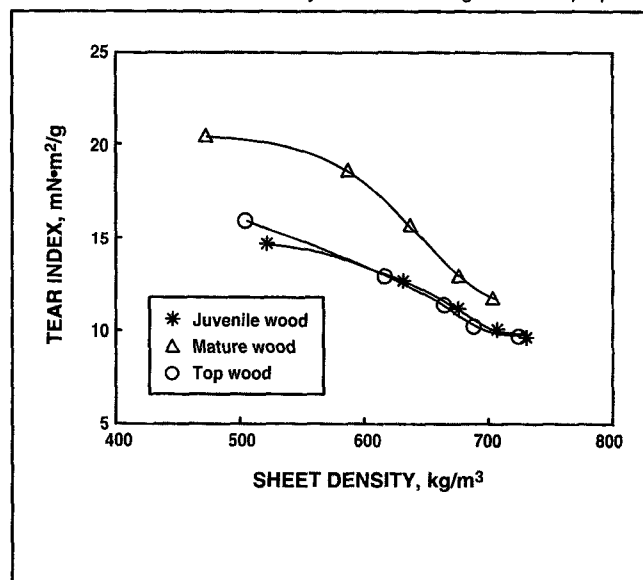
12. Freeness of bleachable-grade kraft pulps



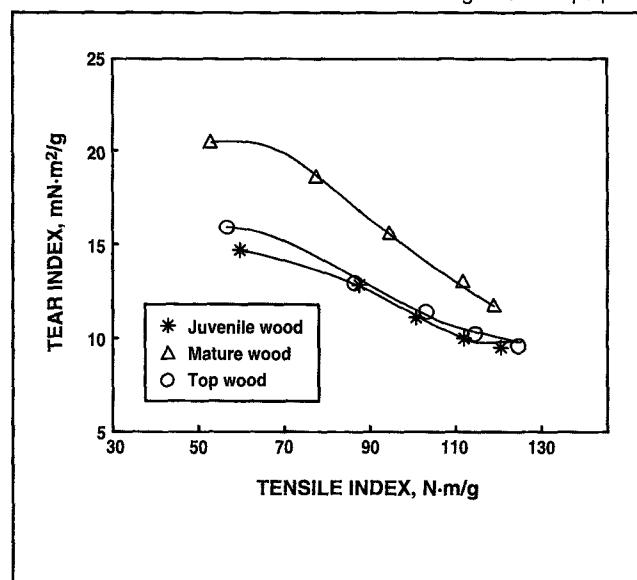
13. Burst index of bleachable-grade kraft pulps



14. Tear index vs. sheet density of bleachable-grade kraft pulps



15. Tear index vs. tensile index of bleachable-grade kraft pulps



Important handsheet properties were analyzed to identify gross differences between tree components. These data, given in **Table IV**, quantify the following narrative of differences and similarities between juvenile wood, mature wood, and top wood pulps.

Properties as a function of PFI revolutions. The rates at which sheet properties developed in bleachable-grade kraft pulps from juvenile wood, mature wood, and top wood—all sites combined—are shown in **Figs. 8–12**.

Bulk properties. At any level of beating, the sheet densities of kraft pulps increased in the order of mature wood less than top wood less than juvenile wood (**Fig. 8**), which agrees with the coarseness values in **Table III**. Handsheets from mature wood kraft pulps were rougher than top wood and juvenile wood pulps (**Fig. 9**) and were more porous, as shown by the air resistance trends in **Table IV**. All three of these trends confirm those found earlier for kraft pulps from second-growth jack pine (7).

Mechanical properties. At all beating levels, handsheets from juvenile wood and top wood kraft pulps showed greater interfiber bonding than those from mature wood pulps, as reflected in values of tensile index (**Fig. 10**) and burst index (**Table IV**) at levels to 6000 revolutions. Kraft pulps from juvenile wood generally had higher stretch than those from mature wood; consequently, the stress-strain factors showed similar behavior (**Table IV**). Zero-span breaking lengths increased slightly with beating in the order of juvenile

Fiber Supply

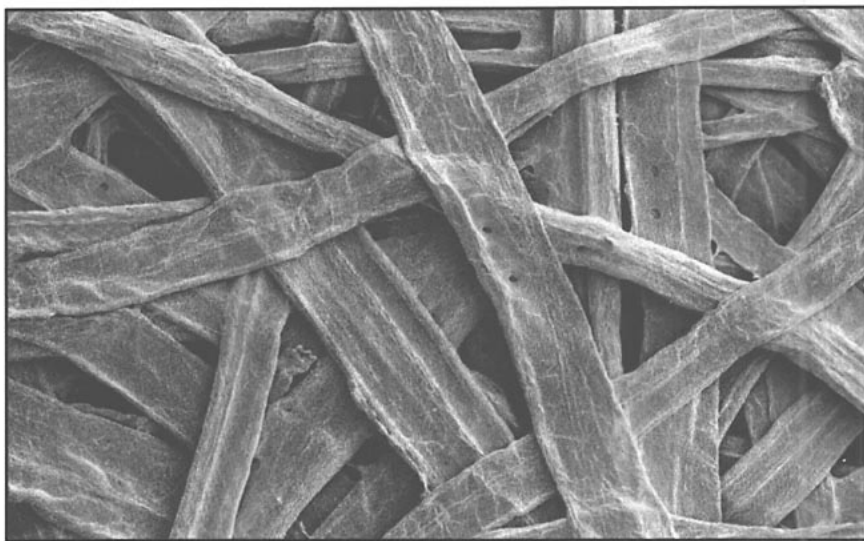
wood less than mature wood less than top wood (Table IV). Tear indexes of mature wood kraft pulps were substantially larger than those of top wood and juvenile wood pulps (Fig. 11); all values decreased with beating and followed earlier trends observed for jack pine (7).

Optical properties. At any level of beating, the scattering coefficients of juvenile wood, mature wood, and top wood kraft pulps were similar.

Pulp freeness as a function of PFI revolutions. At any level of beating up to and including 6000 revolutions, pulp freenesses decreased in the order of mature wood greater than top wood greater than juvenile wood. Within this beating range, mature wood kraft pulps required about 3000 more revolutions than did juvenile wood pulps to reach comparable freeness levels. Thus, at any freeness in the range of 550 mL CSF to 700 mL CSF, shown in Table IV, kraft pulps from juvenile wood gave handsheets which were denser, smoother, and less porous to air than those from mature wood; they also had substantially lower tear indexes. As also found for jack pine (7), the largest freeness drop from 6000 to 12,000 revolutions was observed for mature wood pulps (Fig. 12). The significance of this is not clear.

Properties as a function of sheet density. At sheet densities of 650 kg/m³ or below, handsheets from mature wood pulps were rougher than those from top wood and juvenile wood pulps. Tensile and burst indexes (Fig. 13) of juvenile wood kraft pulps were lower than those from both mature wood and top wood pulps at any given value of sheet density from 550 kg/m³ to 750 kg/m³, the differences becoming larger with increasing values of sheet density. At equivalent low sheet densities, the tear indexes of these lodgepole pine kraft pulps showed mature wood was greater than top wood, which was approximately equal to juvenile wood, but at sheet densities of 750 kg/m³, values of tear index

16. Surface of an unbleached kraft pulp handsheet made from juvenile wood of second-growth lodgepole pine. Fiber coarseness is 203 $\mu\text{g}/\text{m}$. (The marker is 100 μm in length.)



17. Surface of an unbleached kraft pulp handsheet made from mature wood of second-growth lodgepole pine. Fiber coarseness is 281 $\mu\text{g}/\text{m}$. (The marker is 100 μm in length.)



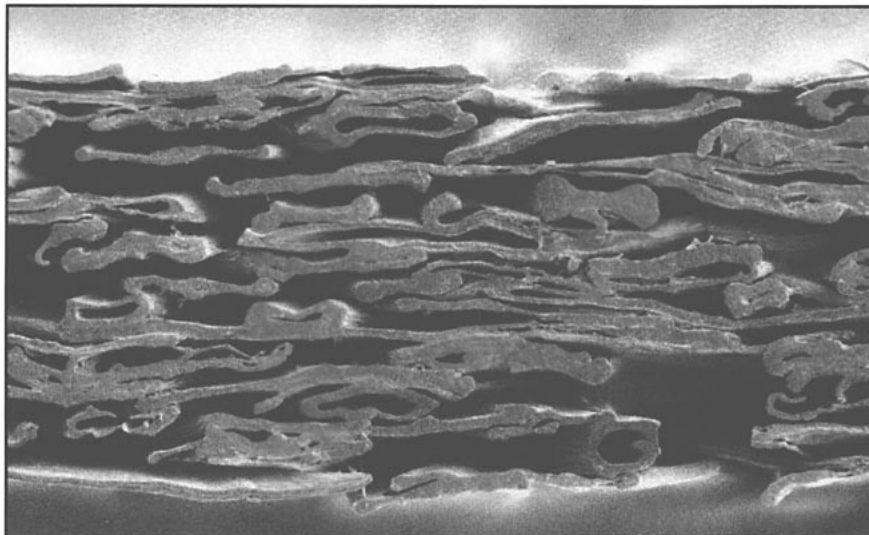
were similar for all three pulp types (Fig. 14).

Tear index vs. tensile index. The tear-tensile index plots for juvenile wood, mature wood, and top wood kraft pulps are shown in Fig. 15; they closely resemble those of Fig. 14. With increasing tensile in the range from 50 N·m/g to 125 N·m/g, decreases in tear index were accompanied by decreases in the tear differences between pulp types.

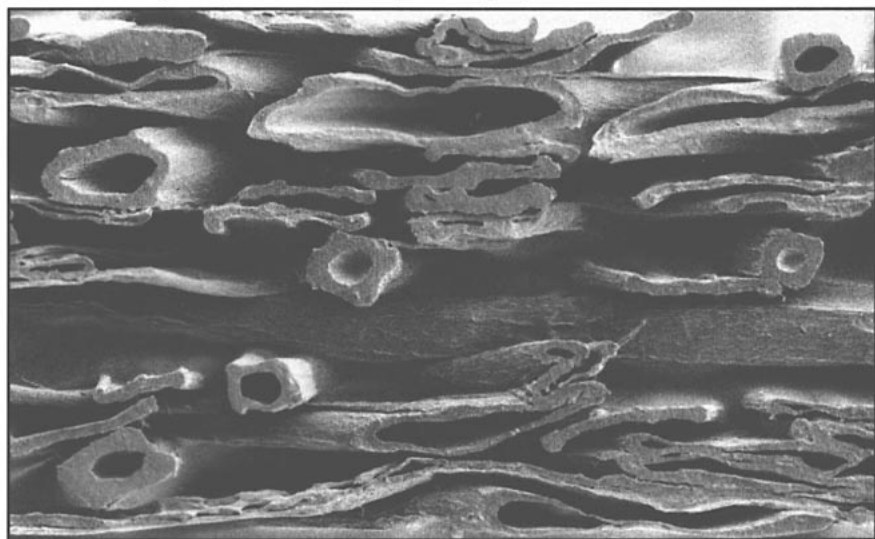
Options for utilization of shorter-rotation lodgepole pine

There will be more options for utilization of future forest crops because of differences in the fiber properties of juvenile and mature wood, and their corresponding effects on the sheet properties of kraft (and mechanical) pulps. Juvenile wood, with its finer fibers, can be obtained from thinnings, from the tops of saw logs, and from the interior core of saw logs from which slabs of mature wood have been removed for manufactur-

18. Typical cross-sectional view of the thin-walled juvenile wood fibers in the kraft pulp handsheet of Fig. 16. (The marker is 10 μm in length.)



19. Typical cross-sectional view of the thicker-walled mature wood fibers in the kraft pulp handsheet of Fig. 17. (The marker is 10 μm in length.)



ing solid products. Kraft pulps from juvenile wood provide sheets that have excellent tensile strength and smoothness, and will therefore be particularly suited, for example, for reinforcing weaker-fiber furnishes for coated paper grades. Additional options include pulping mixtures of juvenile and mature wood chips in varying ratios to produce tailor-made kraft pulps that suit specific customer requirements. At least one mill in western Canada is already doing this based on our original Dou-

glas-fir findings (6). This opportunity is clearly evident from the photomicrographs of the surfaces (Figs. 16 and 17, respectively) and cross sections (Figs. 18 and 19, respectively) of handsheets made from juvenile wood and mature wood kraft pulps with fiber coarseness values of 203 and 281 $\mu\text{g}/\text{m}$, respectively.

Summary and conclusions

The pulping characteristics, yields, and handsheet physical properties

of unbleached kraft pulps from second-growth lodgepole pine trees of low, medium, and high density from two sites in British Columbia and two sites in Alberta have been determined. Evaluations were performed on representative samples of chips cut from butt juvenile wood, butt mature wood, and top wood sections of each of the 12 trees sampled.

The principal conclusions are as follows:

- Yields of bleachable-grade kraft pulps (kappa no. 35) were always lower for juvenile wood relative to those for mature wood from the same tree by an average value of 2.5% o.d. wood. Yields from the top wood of each tree were also higher than those from the corresponding juvenile wood component. These trends reflect the wood chemistry differences reported earlier (8).
- There was no statistical difference between the H factors required to produce juvenile wood and mature wood pulps at kappa no. 35.
- The weighted-average fiber lengths of bleachable-grade kraft pulps increased in the order of juvenile wood less than top wood less than mature wood.
- The pith-to-bark average fiber lengths increased steadily across the juvenile wood and top wood zones for about 40 years, after which they became essentially constant.
- Fibers from juvenile wood kraft pulps were consistently finer than those from their corresponding mature wood pulps.
- Within each tree, kraft pulps from juvenile wood and top wood formed denser sheets, which were smoother and less porous to air than those from mature wood.
- Kraft pulps from top wood and juvenile wood showed better interfiber bonding than those from mature wood pulps. Tensile and

burst indexes (particularly for moderately beaten pulps), stretch, and stress-strain factors were all larger than those from mature wood pulps, but the tear indexes were substantially reduced. Note, however, that the out-of-plane Elmendorf tear test is related only indirectly to end-use performance, because failure occurs most often in an in-plane mode.

- Options for utilizing shorter-rotation lodgepole pine provide excellent potential to produce kraft pulps meeting specific customer needs. 

Literature cited

1. *Reference Tables 1991*, Canadian Pulp and Paper Association, Montreal, 1992.
2. Barbour, R. J. and Hatton, J. V., *Can. For. Ind.* 32(Oct. 1992).
3. Hatton, J. V. and Hunt, K., *1988 CPPA Spring Conference Preprints*, Canadian Pulp and Paper Association, Jasper, AB, Canada.
4. Hatton, J. V. and Hunt, K., *TAPPI 1990 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 861.
5. Hatton, J. V. and Hunt, K., *TAPPI 1989 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 573.
6. Hatton, J. V. and Cook, J., *Tappi J.* 75(1): 137(1992).
7. Hatton, J. V., *Tappi J.* 76(5): 105(1993).
8. Hatton, J. V. and Hunt, K., *TAPPI 1992 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 873.
9. Keays, J. L. and Hatton, J. V., *Tappi* 54(1): 99(1971).
10. Hatton, J. V. and Hunt, K. in *Lodgepole pine: the species and its management, Symposium Proceedings* (D. M. Baumgartner, R. G. Krebill, J. T. Arnott, et al., Eds.), Washington State University, Pullman, WA, 1985, pp. 335-341.
11. Hatch, R. S. and Holzer, W. F. in "Pacific Coast Pulpwoods," Monograph No. 4, TAPPI, Atlanta, 1947, p. 153.
12. Martin, J. S., *Tappi* 32(12): 534(1949).
13. MacLeod, J. M., *Pulp Paper Can.* 87(1): 76(1986).
14. Hatton, J. V. and Keays, J. L., *Pulp Pap. Mag. Can.* 71(11/12):123(1970).
15. Horn, R. A. and Auchter, R. J., *Paper Trade J.* 156(46): 55(1972).
16. Hatton, J. V., *British Columbia Lumberman* 59(6): 64(1975).
17. Hatton, J. V., *Tappi* 53(4): 627(1970).
18. Hatton, J. V. and Hunt, K., *Tappi* 55(1): 122(1972).
19. Baranyay, J. A., Szabo, T., and Hunt, K., *Canadian Forestry Service Inform. Rept. BC-X-86*, Pacific Forest Research Centre, Victoria, BC, Canada, 1973.
20. Keays, J. L. and Szabo, T., *Pulp & Paper* 48(3): 122(1974).
21. Hatton, J. V., Keays, J. L., and Waelti, H., *Pulp & Paper* 50(6): 90(1976).
22. Keays, J. L. and Bagley, J. M., *Tappi* 53(10): 1935(1970).
23. Kesler, R. B., *Tappi* 49(2): 71(1966).
24. Gee, W. Y. and Hatton, J. V., *Tappi J.* 74(2): 221(1991).
25. Box, G.E.P., Hunter, W.G., and Hunter, J.S., *Statistics for Experimenters*, John Wiley & Sons, New York, 1978, pp. 93-104.

The authors gratefully acknowledge the invaluable assistance of the following companies in locating stands, in felling the trees, and for providing the samples used in this study: Crestbrook Forest Industries Ltd., Canfor Corp., and Weldwood of Canada Ltd.

The assistance of Ken Hunt, Vancouver Laboratory, who supervised the field work, was invaluable. The technical expertise of Wayne Richard and the Physical Testing Section, Pointe Claire Laboratory, in beating and handsheet evaluation is much appreciated. The expertise of James Drummond in producing the photomicrographs is acknowledged. Finally, the figures were created by Wyn Walker, Vancouver Laboratory.

Received for review July 19, 1993.

Accepted Jan. 13, 1994.

Presented at the 1993 TAPPI Pulping Conference.