A survey of ClO_2 delignification practices in Canada

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ABSTRACT

Results are reported from a survey of operating conditions in Canadian mills that are producing elemental chlorine-free (ECF) grades of bleached pulp. ECF refers to the complete replacement of chlorine with chlorine dioxide in the first stage of bleaching. Chlorine dioxide delignification is rapidly becoming the common process in the first stage of bleaching. This report documents the practical conditions utilized in actual mill-scale production of ECF pulps.

Application:

Opportunities are identified for cutting the consumption and costs of bleaching chemicals for conventionally delignified softwood kraft pulps.

Chemical pulp bleaching in Canada continues to advance technologically. In 1988, bleach plants began adopting substantial substitution of chlorine dioxide for chlorine. Today, in 1997, all bleach plants in Canada use substantial substitution of chlorine dioxide in the first stage of bleaching (i.e., more than 50%). On a production-weighted basis, pulps produced with chlorine dioxide substitution now average 87% for all bleached chemical pulps. Softwood grades average 90%, and hardwood grades average 79%.

The number of mills practicing complete replacement of chlorine with chlorine dioxide continues to grow. These so-called or "elemental chlorine-free" (ECF) pulps are bleached without elemental chlorine, Cl_2. In 1996, almost 90% of bleach plants in Canada produced ECF pulps, totaling about 8.2 million metric tons of bleached pulp. The ECF pulps now account for 67% of the total Canadian production of bleached chemical pulp. Almost 60% of bleach plants and over 50% of bleached chemical pulp mill sites in Canada use ECF bleaching exclusively.

To keep abreast of the developments in bleaching practice, the CPPA Bleaching Committee issued questionnaires to mills in Canada in 1994, 1995 and 1996. The questionnaires were designed specifically to determine the extent and impact of increased chlorine dioxide substitution and complete replacement of chlorine with chlorine dioxide in the first stage of bleaching. In 1996, the questionnaire was expanded to assess ECF bleaching practices and to determine, if possible, the optimum conditions for maximizing brightness while minimizing costs.

In 1996 the questionnaire was sent to forty-two mills. Thirty-eight mills responded. We used the 1995 survey *(1)* to estimate the pulp production for the mills that did not respond. We also received and analyzed supplemental questionnaires for 36 ECF bleaching lines. Here, we summarize the results of the survey.

PULP BLEACHING IN CANADA

Table I summarizes bleached chemical pulp production in Canada. Most of the pulp is produced to sell as market pulp, and most of the pulp is produced through the kraft process.

Figure 1 shows the changing nature of bleached chemical pulp production since 1990. ECF pulp production continues to rise. As the figure shows, ECF pulp accounted for 67% of bleached chemical pulp produced in Canada in 1996. In 1996, totally chlorine-free (TCF) pulp was produced at only two sulfite mills.

DEVELOPMENT OF ClO_2 SUBSTITUTION

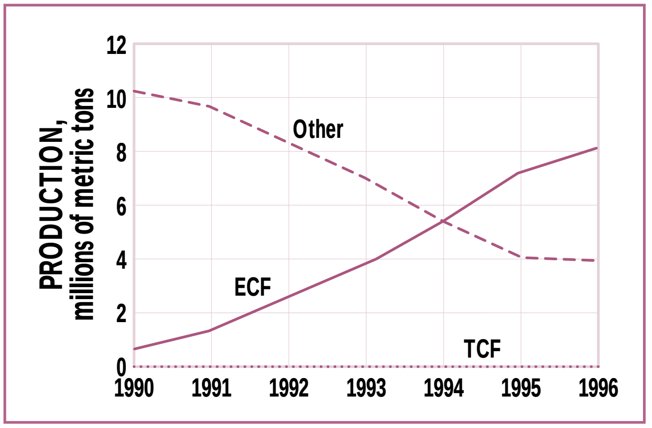
In 1987, only nine bleach plants in Canada were practicing substantial substitution of chlorine dioxide *(2)*. Since 1988, the number of bleach plants practicing substantial substitution has been steadily increasing, as shown in **Fig. 2**. In 1996, all of the bleach plants in Canada practised greater than 50% substitution.

Perhaps even more dramatic is the growth of the practice of complete replacement of chlorine with chlorine dioxide in the first stage of bleaching. In 1989, the number of bleach plants producing ECF pulps began to grow quickly. ECF pulp is now produced at 36 of 42 mill sites and in 47 of 53 bleach plants. Twenty-three mill sites produce ECF grades exclusively.

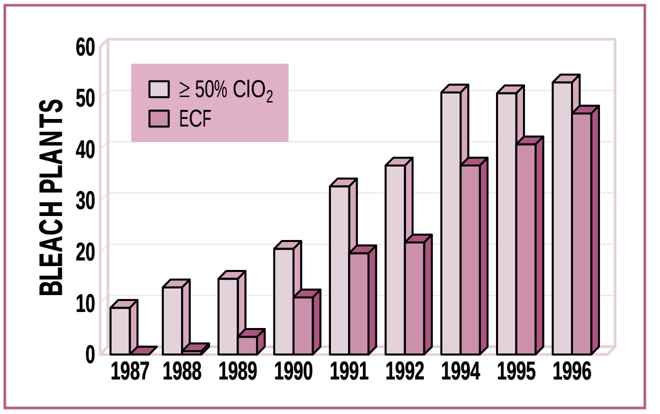
As mentioned, expanded questionnaires were issued to those bleach plants producing ECF pulps. The questionnaires requested information on unbleached pulp, process conditions, chemical consumption, mixing, control strategy, and so on. Responses were received covering 36 bleach plants—29 softwood and 7 hardwood pulp bleaching plants.

This report summarizes the bleaching practices from the softwood bleach plants within two categories, oxygen-delignified and conventionally delignified. These two categories were further subdivided into "low" and "high" categories in regard to the relative chemical consumption.

The database for hardwood pulp was not sufficient to characterize practices. The questionnaires and the full data analysis for both softwood and hardwood pulps can be



1. Production of bleached chemical pulp in Canada



2. Bleach plants that substantially substitute chlorine dioxide have been increasing in number since 1987.

	ECF	TCF	Other*	Total
Hardwood	1.40	0.006	1.57	2.98
Softwood	6.82	0.035	2.42	9.28
Total	8.22	0.041	3.99	12.26

*Pulps bleached with substantial substitution of chlorine dioxide. Softwood and hardwood pulps average 60% substitution.

I. 1996 Canadian bleached chemical pulp production, in million metric tons

obtained from the CPPA Bleaching Committee. The information reported here, along with some additional charts and other tabulated data, can also be found in our earlier paper published in the proceedings for the TAPPI 1996 Pulping Conference *(3)*.

For ECF grades, the dominant sequence is D(E+O+P)DED (**Fig. 3**). Most grades are bleached to high brightness, commonly 88–90% ISO as shown in **Fig. 4**.

UNBLEACHED PULP

Kappa number

The kappa numbers average 28.7 for conventionally delignified pulps and 17.5 for oxygen-delignified pulps on entering the bleach plant.

Oxygen delignification and modified cooking are growing in importance. Twenty-eight percent of the kraft pulp in Canada is now produced by oxygen delignification. This percentage represents 3.5 million metric tons of production. Oxygen delignification of softwoods is now practiced at 11 sites.

Carryover to the bleach plant

Carryover of unwanted chemicals from pulping to the bleach plant (i.e., the first chlorine dioxide stage) is determined by measuring the sodium concentration in the liquor associated with the incoming pulp (unbleached pulp or oxygen-delignified pulp). This measure of carryover is expressed as kilograms of Na_2SO_4 per air-dried metric ton. More recently, mills are beginning to use chemical oxygen demand (COD) to measure carryover of those chemicals that will consume chlorine dioxide in the first stage of bleaching.

As shown in **Figs. 5 and 6**, the carryover ranges from 5 kg to 20 kg per air-dried metric ton for either Na_2SO_4 or COD. The average value of both Na_2SO_4 and COD carryover, for both conventional and oxygen-delignified pulps, is about 8 kg/a.d. metric ton.

OPERATING CONDITIONS

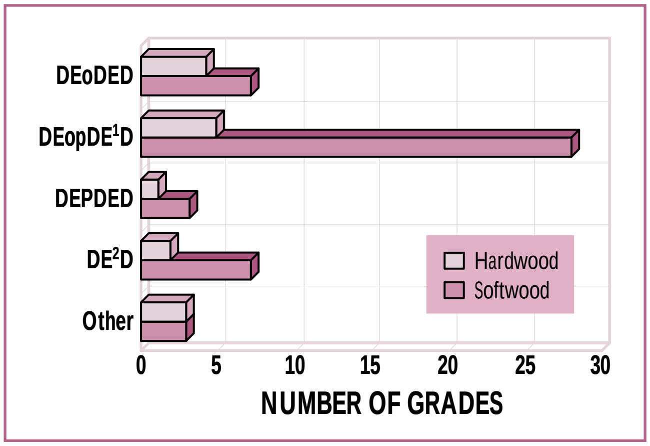
First chlorine dioxide stage, D_0

The typical first stage of chlorine dioxide bleaching is operated at low consistency, reflecting the transition from chlorine to chlorine dioxide. Of the bleach plants, 80% operate at low consistency, and 20% operate at medium consistency. Furthermore, 87% are processes with upflow towers, and only 13% are upflow–downflow towers.

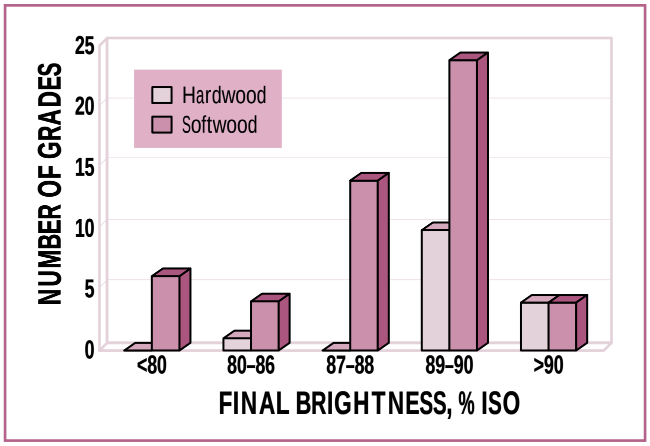
Retention time is 36 min, with a range of 6–120 min. Temperatures average 54°C, ranging from 35°C to 65°C. Residual chlorine dioxide is typically zero. Approximately 80% of oxygen delignification bleach plants and 65% of conventional lines control the end pH at 2.5 by adding H_2SO_4.

Process control in the first stage is dominated by optical and residual sensors before the tower, with 80% of the plants controlling to a compensated brightness setpoint. About 30% of the plants surveyed use a post-tower optical sensor as well. Approximately 30% of the plants control to an extracted kappa number. Of the conventional lines, 35% have kappa number analyzers.

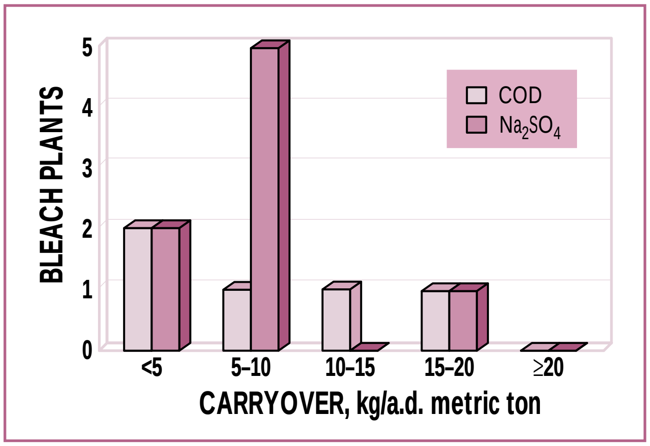
Both mechanical and static mixers are used in various combinations, with the distribution of chlorine dioxide varying widely among mixers. These differences among mills probably arose as different mixing strategies were implemented under different designs for substituting chlorine dioxide. No doubt, differences in associated hydraulic limitations also contributed to the diversity. In short, there is no evidence of a pattern among the mills for the mixing strategy or for chlorine dioxide addition.



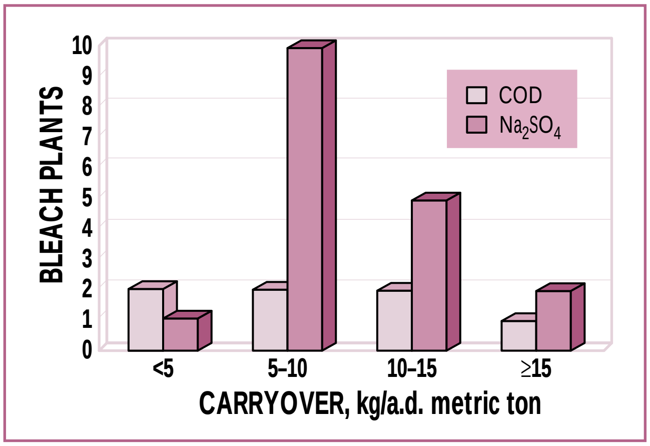
3. Elemental chlorine-free bleaching sequences for hardwoods and softwoods. [[1]May also be (E+P). [2]May also be (E+O) or (E+O+P).]



4. Most grades are bleached to high brightness, with the final brightness most commonly reported to be in the range of 88–90% ISO.



5. Carryover to the bleach plant for oxygen-delignified softwood pulps



6. Carryover to the bleach plant for conventionally delignified softwood pulps

The kappa factor is higher for oxygen-delignified pulps, which average 0.23 as opposed to an average of 0.20 for conventionally delignified pulps. The kappa factor equals the percent equivalent chlorine on pulp divided by the incoming kappa number. (The percent equivalent chlorine on pulp in the first D-stage equals 2.63 times the chlorine dioxide measured as a percent on pulp.)

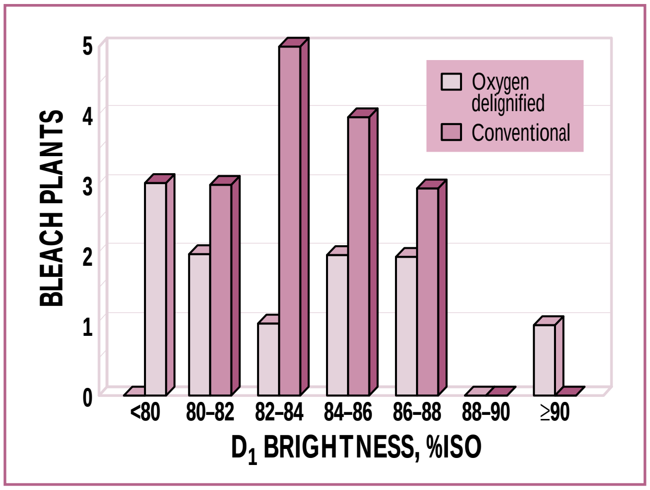
Oxygen-delignified pulps are relatively more difficult to further delignify with chlorine dioxide. This fact is reflected in the higher kappa factor in the first D-stage.

First extraction stage, E+O+P
The retention time for the E+O+P stage is 75 min, with a range of 50–134 min, operating at 75°C, with a range of 55–85°C. Approximately 10% of oxygen delignification bleach plants and 25% of conventional lines utilize Papricycle™ to minimize sodium hydroxide consumption. The ratios of NaOH to equivalent Cl_2 average 0.45–0.48 without Papricycle and 0.25–0.36 with Papricycle. This difference represents a savings of approximately 7–9 kg NaOH/a.d. metric ton.

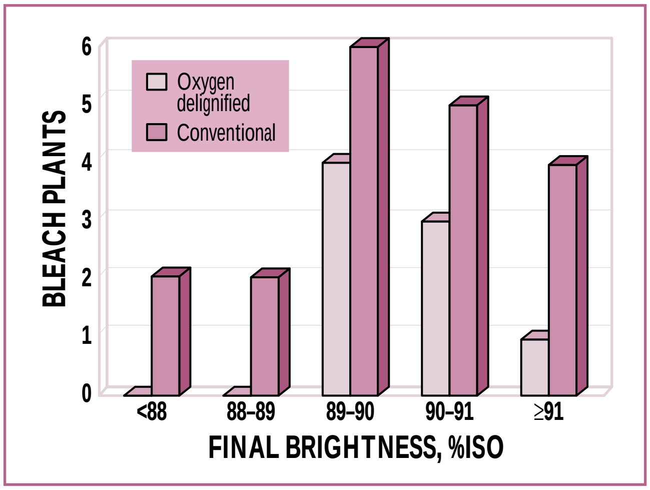
Essentially all stages are controlled to an end pH of 10.5–10.8, with 50% of oxygen delignification lines and 30% of conventional lines controlling to an E+O+P brightness target. Controlling to the E+O+P kappa number is more popular in conventional lines, with 40% of the lines using this parameter, compared to only one oxygen delignification line.

Both hydrogen peroxide and oxygen are used in the extraction stage in 90% of the bleach plants. Oxygen is applied typically at 5.5 kg/a.d. metric ton and hydrogen peroxide is applied typically at 3.4 kg/a.d. metric ton. The E+O+P kappa number for oxygen-delignified pulps averages 3.6, compared to 5 for conventional pulps.

The kappa factor for the first D-stage plus the E+O+P stage is higher for oxygen-delignified pulps. (This kappa factor includes the chlo-



7. Distribution over the bleach plants surveyed for pulp brightnesses in the second chlorine dioxide stage, or the D_1-stage



8. Distribution over the bleach plants surveyed for pulp brightnesses in the final chlorine dioxide stage, or the D_2-stage

rine dioxide in the D_0-stage plus the hydrogen peroxide and oxygen, all expressed as equivalent chlorine.) Oxygen-delignified pulps average 0.39 in kappa factor, while conventionally delignified pulps average 0.30. Delignification is typically 90% in both cases, but with oxygen-delignified pulps it takes more oxidizing chemical equivalents for each unit of kappa number decrease. For oxygen-delignified pulps, it takes 0.47% equivalent chlorine for each unit of kappa number decrease, compared to 0.35% equivalent chlorine for conventional pulps.

Chlorine dioxide brightening: D_1-stage

The average retention time in the D_1-stage is 160 min, with a range of 60–240 min. The operating temperature is 72°C, with a range of 68–81°C. Approximately 40% of oxygen delignification bleach plants and 85% of conventional lines add NaOH to control pH. The upflow pH averages 3.8–3.9, and the end pH is 3.3–3.8.

Using pre-tower optical and residual sensors, most plants control the D_1-stage to a compensated brightness target and an end-of-tower pulp brightness. A chlorine dioxide residual is retained at the end of the stage, typically in amounts ranging from trace quantities to 40 mg/L as measured in the D_1-stage washer vat.

Brightness is widely distributed, as **Fig. 7** shows. D_1-stage brightness averages 84% ISO for oxygen-delignified pulps and 83% ISO for conventional pulps. Chlorine dioxide is applied at 9 kg/a.d. metric ton for oxygen-delignified pulps, compared to 11.3 kg/a.d. metric ton for conventional pulps, reflecting the difference in post-extraction kappa number. The application rate for both pulps is approximately 2.3 kg ClO_2/a.d. metric ton per unit E+O+P kappa, compared to 2.0 for laboratory-generated values *(3)*.

Second extraction stage, E_2

Recently, a number of mills have incorporated so-called "short extraction" stages for the second E stage. In some configurations, NaOH is added directly to the ring dilution at the bottom of the D_1-stage tower, and the short residence time before the pulp is pumped to the D_1-stage washer is used for extraction. The pulp is then washed and forwarded to the D_2-stage. In other configurations, NaOH is added to the washed D_1 pulp, and the residence time in a medium-consistency-pump feed chute is used for extraction. The pulp is not washed in this case, and chlorine dioxide is added directly to the pulp prior to the D_2 tower. Such short extraction stages are found in 20% of the conventional lines and in 40% of the oxygen delignification lines. The retention times for these stages are in the range of 3–25 min.

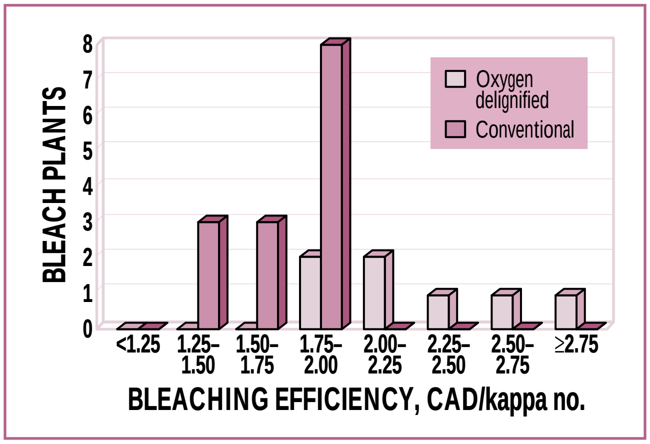
Normal E_2-stage retention time is 75 min, with a range of 45–120 min, at a temperature of 72°C, with a range of 65–85°C. Both the short and long stages are each controlled to an end pH of 10.2–10.3. Approximately one third of both oxygen-delignified and conventional lines add hydrogen peroxide at 1–1.5 kg/a.d. metric ton.

NaOH consumption differs considerably between the short and long stages. The short stages consume 8–10 kg NaOH/a.d. metric ton, as opposed to 3–5 kg/a.d. metric ton for long stages.

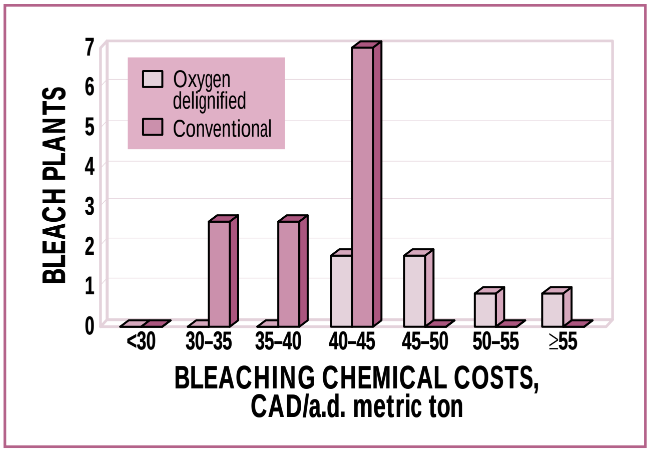
Chlorine dioxide brightening: D_2-stage

The average D_2-stage retention time is 165 min, with a wide range of 60–255 min, operating at an average temperature of 75°C, with a range of 66–82°C. NaOH is usually not added to control pH. The upflow pH averages 4.5, and end pH averages 3.7–3.8.

Few stages are controlled using pre-tower optical and residual sensors. Rather, chlorine dioxide is applied as a percentage on pulp and to a final brightness target. A positive chlorine dioxide residual is retained at the end of the stage, typically in amounts ranging from trace quantities to 40 mg/L as measured in the



9. Bleaching efficiency (bleaching chemical costs in Canadian dollars divided by the kappa number of the unbleached pulp)



10. Bleaching chemical costs (bleaching chemical costs in Canadian dollars per air-dried metric ton)

D_2-stage washer vat.

D_2-stage brightness averages 89.8% ISO for oxygen-delignified pulps and 89.6% ISO for conventional pulps. The distribution is shown in **Fig. 8**. Chlorine dioxide is applied at 2.9 kg/a.d. metric ton for oxygen-delignified pulps, compared to 3 kg/a.d. metric ton for conventional lines. Chlorine dioxide is distributed at a ratio of 3:1 between the D_1 and D_2-stages for oxygen-delignified pulps and at a ratio of 4:1 for conventionally delignified pulps.

	Oxygen Low*	Oxygen High*	Conventional Low*	Conventional High*
Number of bleach plants	5	2	5	5
Kappa no. to D_0-stage	18.4	14.6	28.4	27.6
COD carryover, kg/a.d. metric ton	…	…	…	…
Na_2SO_4 carryover, kg/a.d. metric ton	6	6	8.4	9.1
Retention time, min.	39	13	48	30
Temperature, °C	56	57	53	49
End pH	2.5	2.4	2.4	2.4
ClO_2, kg/a.d. metric ton	15.6	11.1	20.4	21.8
Kappa factor	0.23	0.20	0.19	0.21

* Relative chemical consumption.

II. D(E+O+P)DED bleaching: first chlorine dioxide stage, D_0

OVERALL BLEACHING CHEMICAL CONSUMPTION AND COSTS

The kappa factor for the overall sequence averages 0.57 for oxygen-delignified pulps and 0.44 for conventional pulps. The kappa factor for the overall sequence is the sum of chlorine dioxide in all stages plus oxygen and hydrogen peroxide in the extraction stages, all expressed as the percent equivalent chlorine on pulp divided by the kappa number of the unbleached pulp.

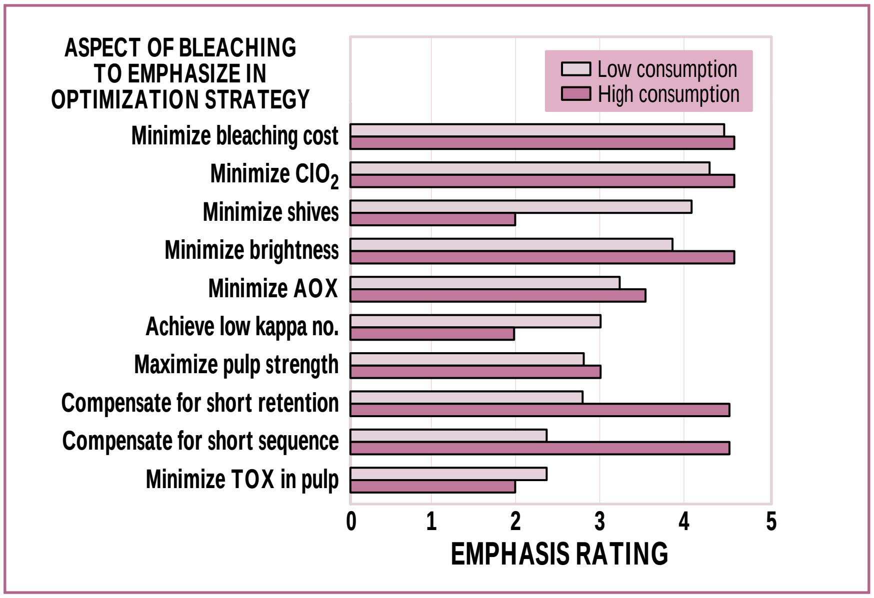
Bleaching efficiency is measured as bleaching chemical costs divided by the kappa number of the unbleached pulp. In terms of bleaching efficiency, the oxygen-delignified pulps average 2.31 CAD (Canadian dollars) per unit of unbleached-pulp kappa number, while conventional pulps average 1.53 CAD per unit to achieve 90% ISO brightness. (Exchange rate: 1.37 CAD = 1.00 USD) **Figure 9** shows the breakdown of the data for bleaching efficiency.

Although the overall kappa factor is higher and the bleaching efficiency is lower for oxygen delignification, the cost of bleaching is lower. The reason is that the unbleached pulps are lower in kappa number for the plants bleaching oxygen-delignified pulps. The average cost for bleaching chemicals for oxygen-delignified pulps was 37.20 CAD/a.d. metric ton, compared to 46.44 CAD/a.d. metric ton for conventional pulps, a difference of 9.24 CAD/a.d. metric ton. **Figure 10** shows the breakdown of the data for bleaching chemical costs. (Assumed costs of bleaching chemicals in Canadian dollars: ClO_2 @ \$1/kg, H_2O_2 @ \$1/kg, NaOH @ \$0.34/kg, O_2 @ \$0.05/kg. Excludes cases with Papricycle).

OPTIMIZATION ANALYSIS OF D(E+O+P)DED BLEACHING

Database

We sorted and analyzed the data supplied both on the nine oxygen-delignified softwood lines and on the twenty conventional softwood lines to see if optimum practices could be determined. The data were sorted by relative chemical consumption. We asked, in other words, which mills



11. Summary of relative emphasis on various aspects of optimization for low- and high-consumption plants bleaching oxygen-delignified softwood pulps

	Oxygen		Conventional	
	Low	High	Low	High
Number of bleach plants	5	2	5	5
Kappa no.	3.7	5.0	5.0	5.0
Brightness, % ISO	55	62	54	54
Retention time, min.	89	60	86	79
Temperature, °C	73	76	79	75
NaOH, kg/a.d. metric ton	16.8	16.6	17.4	21.6
NaOH/equivalent Cl_2				
With Papricycle	0.25	…	0.26	0.20
Without Papricycle	0.46	0.56	0.37	0.45
Oxygen addition, kg/a.d. metric ton	4.2	5.6	5.1	4.8
H_2O_2 addition, kg/a.d. metric ton	3.2	1.8	2.6	2.9
End pH	10.4	10.8	10.7	10.5
Delignification, %	82	71	83	83
Kappa factor[a]	0.36	0.39	0.29	0.31
Change in % eq. Cl_2 per change in kappa no. unit[b]	0.40	0.57	0.33	0.33

[a]Sum of chlorine dioxide in the first stage plus oxygen and hydrogen peroxide in extraction, all expressed as % equivalent chlorine on pulp divided by the kappa number of the unbleached pulp.
[b]All oxidizing chemicals in the first chlorine dioxide and the first extraction stages, expressed as % equivalent chlorine divided by the change in kappa number (i.e., the kappa number of the unbleached pulp minus the kappa number after extraction).

III. D(E+O+P)DED bleaching: first extraction stage, E_1

used the least amounts of oxidizing chemicals on unbleached pulp of the same kappa number to reach the same final brightness?

As mentioned, the database revealed two groups based on chemical consumption. For the plants bleaching oxygen-delignified pulps, there were five lines with relatively low chemical consumption and two lines with relatively high chemical consumption. Similarly, those plants bleaching conventionally delignified pulps fell into two groups as well: five lines with low chemical consumption and five with high consumption. Averages for the four categories are presented in **Tables II–VII**.

Oxygen-delignified pulps
Through the questionnaire, each bleach plant was assessed to determine what each was optimized to achieve. As shown in **Fig. 11**, there were differences in emphasis between the bleach plants having low chemical consumption and those plants having relatively high consumption.

All bleach plants emphasized the importance of minimizing bleaching costs and the consumption of chlorine dioxide. However, the high-consumption bleach plants had greater emphasis on maximizing brightness and on compensating for short retention times and short sequences. The need to minimize shives was more important, on the other hand, in the low-consumption bleach plants.

Kappa factor. The kappa factor in the D_0 stage is lower for the high-consumption bleach plants than it is for the low-consumption plants. This difference probably reflects the short retention times for the high-consumption lines (6 and 20 min, respectively). However, after the E+O+P stage and the D_1-stage, the kappa factor for the high-consumption bleach plants becomes greater than that for low-consumption plants.

In particular, chlorine dioxide application in the D_1 and D_2-stages is greater for the high-consumption bleach plants, as shown in **Fig. 12**. The greater use of chlorine dioxide in these two stages probably goes to compensate for the short retention times through the different stages of the sequence, as indicated in the tables.

Brightness development. The high-consumption bleach plants emphasized maximizing final brightness to a greater extent than did the low-consumption bleach plants. As shown in **Fig. 13**, the high-consumption bleach plants achieved higher final brightness, at 90.8% ISO as opposed to 89.5% ISO. The effort to achieve such a high brightness with short retention time may explain the relatively higher chemical consumption in these bleach plants.

Conventionally delignified pulps

As shown in **Fig. 14**, there were differences in emphasis between the low-consumption and the high-consumption bleach plants for conventionally delignified pulps as well. The low-consumption plants emphasized minimizing bleaching cost and minimizing chlorine dioxide consumption, while the high-consumption bleach plants emphasized maximizing brightness and maximizing pulp strength.

Kappa factor. The kappa factor after each stage is consistently higher for the high-consumption bleach plants, as shown in **Fig. 15**. The kappa factor in the D_0-stage and after E+O+P is 7–10% greater with the high-consumption bleach plants. After the D_1-stage, the difference increases to 15%, and it increases to 17% by the end of the sequence.

Chlorine dioxide application in the D_1 and D_2-stages is greater for the high-consumption bleach plants, as shown in **Fig. 16**. The greater application of chlorine dioxide might serve to compensate for the shorter retention times in the D_1-stage. This explanation is not readily apparent from the averages given in the Table IV: 158 min for low-consumption plants vs. 142 min for high-consumption plants. These averages do not reflect a major difference in the retention times, as four of the five low-consumption bleach plants had 3-h towers and four of the five high-consumption bleach plants had 2-h towers.

Brightness development. Brightness development across the bleach plant was similar for the cases of low and high chemical consumption. In both cases, unbleached pulp of kappa no. 28 was bleached to 89.5% ISO brightness. However, the low-consumption bleach plants achieved the same brightness with 17% less oxidizing equivalents.

Bleaching chemical cost. For oxygen-delignified pulps, despite the relatively high consumption of chemicals, the bleaching costs for the high-consumption lines was lower than for the low-consumption

	Oxygen		Conventional	
	Low	High	Low	High
Number of bleach plants	5	2	5	5
Retention time, min.	175	130	158	142
Temperature, °C	73	74	72	68
Upflow pH	4.2	…	4.0	3.8
End pH	3.9	…	3.3	3.0
Brightness, % ISO	84.8	83.5	82.9	83.6
ClO_2, kg/a.d. metric ton	8.7	9.8	10.4	13.9
NaOH, kg/a.d. metric ton	0.46	0	…	…
H_2SO_4, kg/a.d. metric ton	0	0	…	…

IV. D(E+O+P)DED bleaching: first ClO_2 brightening stage, D_1

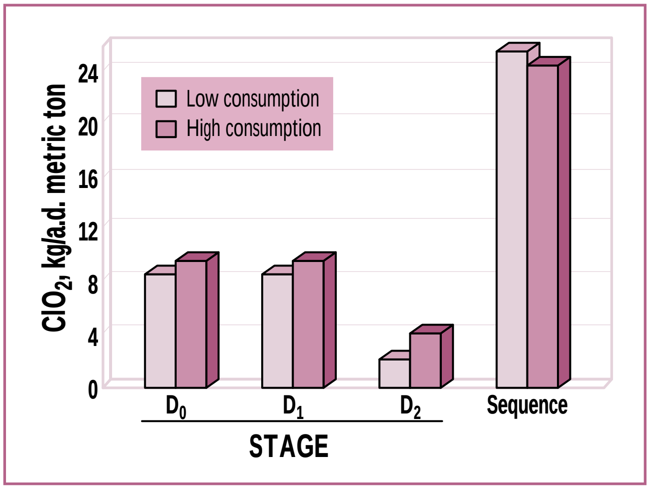
	Oxygen		Conventional	
	Low	High	Low	High
Number of bleach plants	5	2	5	5
Retention time, min.				
Conventional stage	67	…	72	96
Short stage	3	7.5	5	…
Temperature, °C	68	73	70	70
NaOH, kg/a.d. metric ton				
Conventional stage[a]	2.6	…	4.5	5.3
Short stage[b]	9.0	8.8	10	…
H_2O_2,[c] kg/a.d. metric ton	0.8	…	0.7	1.0
End pH	10.4	10.3	10.3	10.3
Brightness, % ISO	82.9	…	81.0	…

[a]DED. [b](D_n)D. [c]When used.

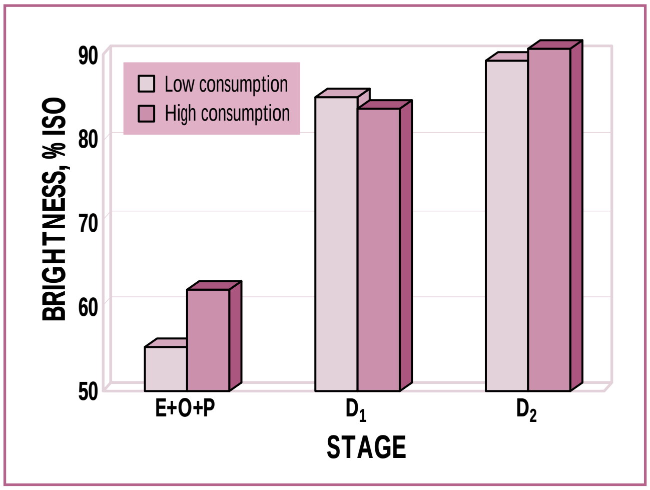
V. D(E+O+P)DED bleaching: second extraction stage, E_2

	Oxygen		Conventional	
	Low	High	Low	High
Number of bleach plants	5	2	5	5
Retention time, min.	185	110	164	165
Temperature, °C	71	75	78	72
Upflow pH	4.2	5.0	4.4	4.4
End pH	3.9	3.2	3.5	3.9
Brightness, % ISO	89.5	90.8	89.8	89.5
ClO_2, kg/a.d. metric ton	2.3	4.2	2.5	3.8

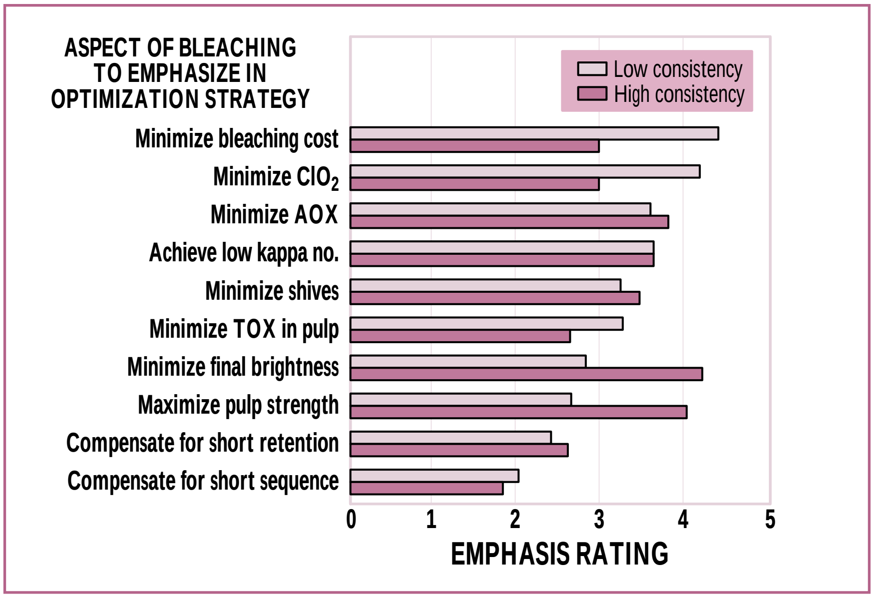
VI. D(E+O+P)DED bleaching: second ClO_2 brightening stage, D_2



12. Distribution of chlorine dioxide consumption for the low- and high-consumption plants bleaching oxygen-delignified softwood pulps



13. Brightness development for oxygen-delignified softwood pulps in the low-and high-consumption plants



14. Summary of relative emphasis on various aspects of optimization for low- and high-consumption plants bleaching conventionally delignified softwood pulps

bleaching lines. These costs per air-dried metric ton averaged 35.7 CAD for the low-consumption lines and 34.3 CAD for the high-consumption lines.

KEYWORDS

Alkaline pulps, bleaching, chemical consumption, chemical pulps, chemical treatment, chlorine dioxide, costs, kraft pulps, mills (factories), oxides, plant departments, pulp mills, pulps, softwood pulps, surveys.

This difference is due to the substantially lower kappa number for the high-consumption case—i.e., 14.6 as opposed to 18.4. The bleaching chemical cost advantage for the grades of low kappa number was 1.40 CAD/a.d. metric ton. This amount is less than would be expected based simply on the kappa number of unbleached pulp. This divergence probably results from the lower bleaching efficiency and the effort to achieve high brightness.

For conventionally delignified pulps, the low-consumption bleaching lines achieved a bleaching cost advantage of approximately 5 CAD/a.d. metric ton compared to the high-consumption bleaching lines. These costs per air-dried metric ton averaged 46 CAD for the low-consumption lines and 51 CAD for the high-consumption lines.

SUMMARY

The replacement of chlorine dioxide for chlorine in the first stage of bleaching is fully compatible with producing market pulps of 89–90% ISO brightness. Oxygen-delignified softwood pulps require more oxidizing equivalents per unit of kappa number in the unbleached pulp.

On the whole, oxygen-delignified pulps have an advantage in bleaching chemical costs over conventional bleached pulps. This advantage is roughly 9.24 CAD per air-dried metric ton of pulp. Finally, operating with optimized chemical consumption can provide bleaching cost advantages of 5 CAD/a.d. metric ton for conventional pulps. **TJ**

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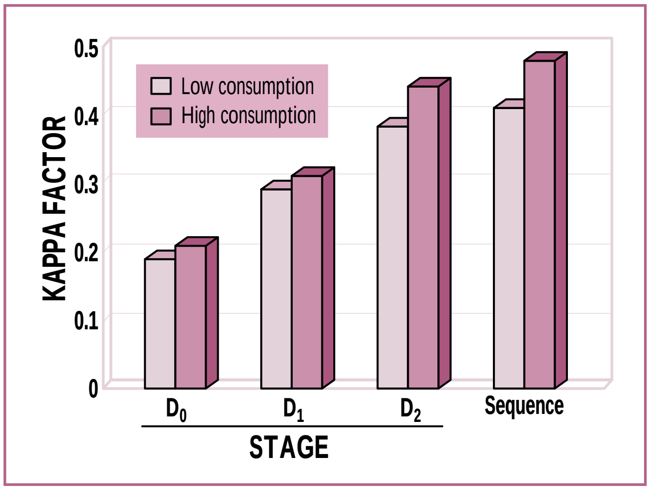
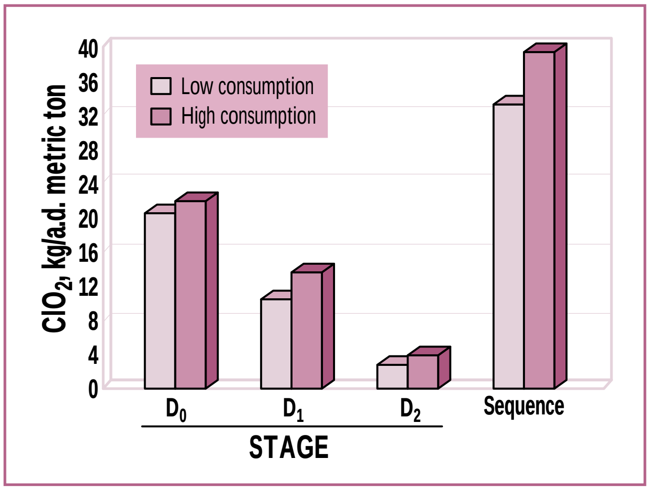


15. Cumulative kappa factors after each stage for conventionally delignified softwood pulps in the low- and high-consumption plants



16. Distribution of chlorine dioxide for the low- and high-consumption plants bleaching conventionally delignified softwood pulps

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	Oxygen Low	Oxygen High	Conventional Low	Conventional High
Number of bleach plants	5	2	5	5
ClO_2, kg/a.d. metric ton	26.1	25.0	33.3	39.6
O_2, kg/a.d. metric ton	4.2	5.6	5.1	4.8
H_2O_2, kg/a.d. metric ton	3.5	1.8	2.8	3.3
NaOH, kg/a.d. metric ton[a]	24.3	21.7	26.7	33.2
Sequence kappa factor[b]	0.51	0.65	0.41	0.48
Cost, CAD/a.d. metric ton[c]	35.68	34.30	46.44	51.83
Efficiency, CAD/kappa no.	2.07	2.40	1.53	1.87
Final brightness, % ISO	89.5	90.8	89.8	89.5

[a]Excludes cases with Papricycle.
[b]Sum of chlorine dioxide in all stages plus oxygen and hydrogen peroxide in extraction stages, all expressed as % equivalent chlorine on pulp divided by the kappa number of the unbleached pulp.
[c]Assumed costs in Canadian dollars: chlorine dioxide at 1.00 CAD/kg, hydrogen peroxide at 1.00 CAD/kg, sodium hydroxide at 0.34 CAD/kg, oxygen at 0.05 CAD/kg. Excludes cases with Papricycle.

VII. Overall chemical consumption, costs, and efficiency of D(E+O+P)DED bleaching

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