Optimization of ECF bleaching of kraft pulp: Part 1. Optimal bleaching of hardwood pulps made with different alkali charges

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ABSTRACT: In an earlier modeling study, we showed that when a hardwood kraft pulp is bleached in the $D_0(EO)D_1ED_2$ sequence with a D_0 stage kappa factor of 0.20, the brightness of the pulp emerging from the D_2 stage can be accurately predicted from the brightness of the pulp entering that stage. The entering brightness, in turn is a well-defined function of the ratio of the D_1 stage ClO_2 charge to the (EO) stage kappa number. In the present study, we use the results of pulping and bleaching experiments on southern U.S. red oak chips to extend the model to account for the effect of changing the D_0 kappa factor and use it to assess the effect of digester alkali charge on pulp bleachability. We also show how this approach can be used to minimize the total ClO_2 requirement for any desired final brightness and to optimize the allocation of ClO_2 to the three D stages of the D(EO)DED sequence of the two D stages of the D(EO)D sequence. Among the conclusions resulting from application of the model are that the combination of high effective alkali and high D_0 kappa factor gives pulp with a higher final brightness ceiling than any other combination, but that for brightness targets of 91 or lower, the combination of low effective alkali and low kappa factor is the most economical.

Application: The results of this study should help mills use the least amount of ClO_2 to efficiently achieve any desired final pulp brightness.

For each stage of a multistage kraft pulp bleaching sequence, there is a relationship between the entering pulp properties, the conditions prevailing within the stage, and the properties of the pulp leaving it. We can describe this relationship by a mathematical model, the output of which can serve as one of the necessary inputs to a similar model of the following stage. A collection of such models, one for each stage of the sequence, constitutes a predictive model of the entire sequence.

To provide a complete description of the bleaching process, each of the component single-stage models would need to account for the effects of the composition of the entering pulp, the composition of the liquid phase mixed with the pulp, flow patterns within the mixer and bleaching tower, concentration gradients throughout the system, temperature, and retention time. Such models would obviously be exceedingly complex and virtually impossible to derive. A more realistic approach involves adopting simplifying assumptions. For example, Wang and coworkers [1] lumped chemical kinetics and mass transfer and used kinetic expressions derived from low-consistency experiments in which the pH and bleaching agent concentrations were held constant. Earlier, Axegård, and coworkers [2] had used similar data to create a model of the DED partial sequence as applied to pulp prebleached in an O(C+D)E partial sequence. Both groups assumed that such expressions were applicable to the real situation, in which the pH and bleaching chemical concentrations change continuously as a result of chemical consumption in the bleaching reactions.

Because they incorporate kinetic expressions and flow pattern assumptions, models of this kind are, in principle, capable of simulating the dynamic behavior of the bleach plant, a desirable feature for process control applications. However, this capability comes at a price: a high degree of complexity, a large number of parameters, and a demanding requirement for tuning and validation. Keski-Säntti and coworkers [3] adopted an alternative approach, using neural networks to infer the needed relationships from mill operating data. Among the virtues of this method are its high degree of relevance to the particular installation on which it is based and the fact that it does not rely on the availability of laboratory-derived kinetic relationships and assumptions concerning their applicability in the field. On the other hand, the predictive ability of the resulting model is limited to the ranges of the operating variables represented in the operating data used. This is a significant limitation because it is possible, and perhaps even likely, that optimal operating conditions lie outside these ranges. Such models are therefore limited in their ability to optimize the system.

For applications where it is not necessary to simulate process dynamics, much simpler steady-state models suffice. Among the applications of steady-state models is the determination of optimum set points for chemical dosage controllers, which is equivalent to optimizing the allocation of chemicals to the different stages of the sequence for any desired final brightness. Another application of steady-state bleach plant models is as a basis for comparison of the bleachability characteristics of different types of pulp in terms of their minimum chemical requirement to attain a given set of final product properties, such as fully bleached brightness, content of nonfibrous contaminants, brightness stability, etc.

In an early study [4], we identified a broadly applicable equation that describes brightness development in ClO_2 bleaching stages. Subsequently [5], we incorporated it into a full-sequence model for the $D_0(EO)D_1ED_2$ bleaching of a hardwood kraft pulp. The latter work showed that when the pulp was bleached with a D_0 stage kappa factor (KF) of 0.20, the brightness of the pulp emerging from the D_2 stage can he accurately predicted from the brightness of the pulp entering that stage. The entering brightness, in turn, was shown to he a well-defined function of the ratio of the D_1 stage ClO_2 charge to the (EO) stage kappa number. The model incorporating these relationships was used to determine the optimum allocation of ClO_2 to the D_1 and D_2 stages and the minimum total ClO_2 requirement for any desired final brightness.

Since then, Hart and Connell [6] have used this model, with suitable adjustment of its parameters, to optimize unbleached kappa number with respect to the combined costs of wood and bleaching chemicals, for various brightness targets. Their work validates the model and illustrates how its site-specific application can yield benefits in the form of reduced operating costs. More recently, Dumont et al. [7] have used the same equations to illustrate an approach for determining optimal ClO_2 dosage controller set points.

In this study, we extend the model to account for the effect of changing the D_0 KF and use it to assess the effect of digester alkali charge on pulp bleachability. We also show how this approach can he used to unambiguously characterize pulp bleachability, minimize the total ClO_2 requirement for any desired final brightness, and optimize the allocation of ClO_2 to the three D stages of the D(EO)DED sequence or the two D stages of the D(EO)D sequence.

EXPERIMENTAL

We used red oak chips provided by a southern U.S. mill. Pulps were prepared in an M/K Systems 10-L laboratory digester, using 30% sulfidity liquor and a temperature schedule that consisted of a 110-min rise from ambient temperature to a maximum cooking temperature of 170°C. Synthetic pulping liquors were prepared from sodium hydroxide and sodium sulfide. Pulps with a kappa number of 14 were prepared with two different effective alkali (EA) charge levels, 13.6% and 17.9%, expressed as Na_2O based on o.d. wood weight. The pulps were screened on a laboratory flat screen having 0.008 in. slots. Pulps from four cooks with EA levels ranging from 13.5% to 13.7% and H-factors from 993 to 1025 were combined to give the low-EA pulp. Pulp from a cook with 18% EA and H-factor 350 and one from a cook with 17.8% EA and H-factor 375 were combined to give the high-EA pulp.

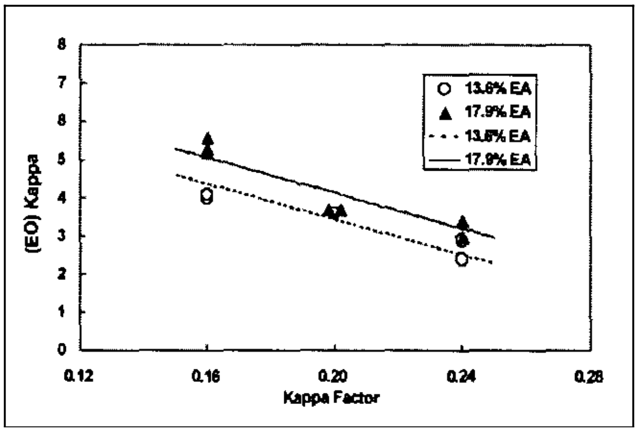
We used a $D_0(EO)D_1ED_2$ bleaching sequence. The pulp was thoroughly washed between stages. The ClO_2 charge in the D_0 stage was chosen to give one of three specified KFs: 0.16, 0.20, or 0.24. For example, when the KF was 0.20, the amount of ClO_2 charged was equivalent to a chlorine charge numerically equal to 20% of the kappa number of the unbleached pulp, The first stage was carried out for 30 min at 45°C in a Quantum mixer, with an exit pH in the range 1.8–2.3. The (EO) stage was conducted at 70°C and 10% consistency in a horizontal shaft peg mixer rotating at 200 rpm for 60 min. The oxygen pressure, initially at 60 psig, was decreased by 12 psig every 5 min during the first 30 min. The alkali charge was equal to 50% of the active chlorine charge in the D_0 stage, giving an exit pH of 11 or higher. The D_1 and D_2 stages were conducted for 180 min at 70°C, and the E_2 stage was at 70°C for 60 min, with an NaOH charge of 0.4%. After the (EO) stage, each pulp was divided into three equal portions, which were then bleached in the D_1 stage with 0.2%, 0.6%, and 1.8% ClO_2. Each of the three resulting D, pulps was then extracted with caustic and further subdivided for bleaching with 0.1%, 0.3%, and 0.9% ClO_2 in the D_2 stage.

Measurements included pH and residual chemical at the end of each stage, the kappa number after the (EO) stage, and the brightness after the D_1 and D_2 stages. We determined kappa number and ISO brightness according to TAPPI Test Methods

RESULTS AND DISCUSSION

D_0 stage model

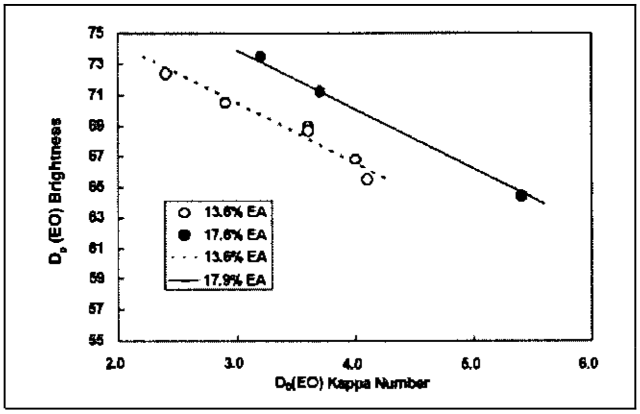
Figure 1 presents the results of $D_0(EO)$ bleaching of the two pulp types. Despite the well known curvilinear dependence of extracted kappa number on KF [6], the relationship was adequately represented by a linear regression relationship over the range of KFs studied in the present case. The high-alkali pulps were more difficult to delignify in the first two stages than those produced with a lower digester alkali charge.



1. Dependence of (EO) kappa number on D_0 stage kappa factor.

The following equation describes the curves shown in Fig. 1;

$$y_o = b_{00} - b_{10} \cdot f \tag{1}$$



2. D_0(EO) brightness-kappa number relationship.

in which y_0 = kappa number after the D_0 and (EO) stages and f = D_0 stage KF.

In this equation, and in the other equations of this paper, the first subscript identifies the order of the constant within the equation and the second is the same as that of the stage it refers to (e.g., 0 for D_0, 1 for D_1)

For the low-EA and high-EA pulps, regression analysis gave b_{00} values of 8.08 and 8.78, respectively. The value of b_{10} was 23.2 for both pulps.

Figure 2 shows the relationships between brightness and kappa number for pulps exiting the (EO) stage. The high-EA pulps, despite their higher kappa number, were brighter than their low-EA counterparts. On the average, they were 3.5 points brighter.

D_1 stage model

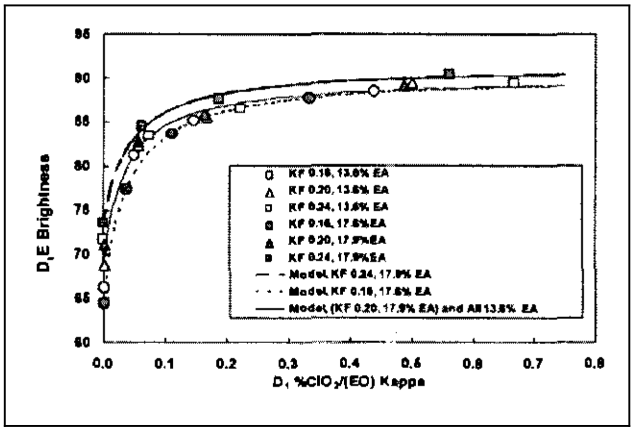
The results of experiments in which the low-EA and high-EA pulps were fully bleached are presented in **Tables I** and **II,** respectively.

After D_0(EO)			After D_1E			After D_2		
KF	Brightness	kappa	ClO_2, %	D_1 End pH	Brightness	ClO_2, %	End pH	Brightness
0.16	66.2	4.1	0.2	4.8	81.3	0.1	4.3	85.6
						0.3	4.2	87.9
						0.9	3.2	89.9
			0.6	4.3	85.2	0.1	4.3	89.4
						0.3	4.5	90.3
						0.9	3.9	91.0
			1.8	2.9	88.5	0.1	4.4	91.4
						0.3	5.2	92.0
						0.9	4.8	92.0
0.20	68.8	3.6	0.2	-	82.4	0.1	4.3	87.4
						0.3	4.2	89.1
						0.9	3.6	90.1
			0.6	5.6	85.6	0.1	4.5	89.1
						0.3	4.4	90.2
						0.9	3.9	90.9
			1.8	3.3	89.5	0.1	4.6	91.4
						0.3	4.9	92.0
						0.9	4.7	92.1
0.24	71.7	2.7	0.2	3.7	83.4	0.1	3.9	88.2
						0.3	3.9	90.1
						0.9	3.3	90.6
			0.6	3.7	86.5	0.1	4.7	90.5
						0.3	4.2	91.0
						0.9	4.3	91.3
			1.8	3.3	89.4	0.1	4.2	91.8
						0.3	4.7	91.8
						0.9	4.0	92.2

I. Bleaching data for low-alkali pulp.

After D_0(EO)			After D_1E			After D_2		
KF	Brightness	kappa	ClO_2, %	D_1 End pH	Brightness	ClO_2, %	End pH	Brightness
0.16	64.4	5.4	0.2	4.8	77.4	0.2	4.5	84.2
						0.6	3.2	86.7
						1.8	—	87.9
			0.6	3.9	83.7	0.2	4.3	89.0
						0.6	2.8	90.5
						1.8	4.5	91.1
			1.8	4.0	87.8	0.2	4.2	91.2
						0.6	3.8	91.2
						1.8	4.5	91.3
0.20	71.2	3.7	0.2	4.5	82.8	0.2	4.0	87.4
						0.6	3.7	90.5
						1.8	3.5	91.1
			0.6	4.0	86.0	0.2	4.1	91.3
						0.6	4.7	91.8
						1.8	5.8	92.1
			1.8	4.1	89.2	0.2	4.5	92.0
						0.6	4.6	91.9
						1.8	4.9	92.5
0.24	73.5	3.2	0.2	4.7	84.5	0.2	4.3	89.1
						0.6	3.3	90.5
						1.8	3.9	92.0
			0.6	3.7	87.6	0.2	4.2	91.6
						0.6	4.1	91.9
						1.8	4.7	92.4
			1.8	4.4	90.4	0.2	4.5	91.7
						0.6	4.6	92.7
						1.8	4.8	92.8

II. Bleaching data for high-alkali pulp.



3. D_1E brightness values as functions of D_1 multiple. The top curve is the regression model applicable to the high alkali pulps after a 0.24 kappa factor D_0 stage and the bottom one is the model for the high alkali pulps after a 0.16 kappa factor D_0 stage. The middle curve models all other combinations of alkali and kappa factor studied.

The brightness after the D_1 and E stages correlates closely with the ClO_2 charge in the D_1 stage divided by the kappa number ofthe pulp entering the D_1 stage. This quotient may be referred to as the "D_1 multiple." Note that the ClO_2 charge is expressed as ClO_2, not as equivalent chlorine, when calculating the D_1 multiple.

In an earlier study [5], we accurately described the relationship between D_1 brightness and D_1 multiple using an exponential relationship of the type,

$$y_1 = b_{01} + b_{11} \cdot [1 - \exp(-b_{21} \cdot m)] \tag{2}$$

in which y_1 = brightness after the D_1 stage and m = D_1 stage ClO_2 charge multiple.

The constants b_{01}, b_{11}, and b_{21} are, respectively, the brightness ofthe pulp leaving the (EO) stage, the maximum brightness gain achievable in the D_1 stage, and a constant that is characteristic of the relative rate of approach to this maximum as the chemical charge is increased.

Attempts to fit this equation to the data of Tables I and II met with only moderate success, since the current D_1E brightness data do not display such a well-defined brightness ceiling as was apparent in the data for the pulp studied earlier. In both cases, as the ClO_2 charge was increased, the brightness increased sharply at low charges and leveled off rapidly as the charge was further increased. However, in contrast to the earlier case, the brightness ofthe present pulp continued to increase, albeit very slowly, with further increases in chemical charge. In the present work we therefore used an alternate model for the D_1 stage. This model is based on the following equation:

$$y_1 = c_{01} - c_{11} / (m + c_{21}) \tag{3}$$

in which y_1 = brightness after the D_1 and E stages and m = D_1 stage ClO_2 charge multiple.

The constants in this equation are designated by the letter "c" to avoid confusion with those of Eq. 2. The constant c_{01} is the ultimate brightness ceiling, which occurs at higher charge levels than in cases that are described by Eq 2. The constants c_{11} and c_{21} together determine the brightness of the pulp entering the stage and the dependence of the slope of the response curve on the charge multiple. The brightness of the pulp entering the stage is $c_{01} - c_{11}/c_{21}$. At a charge multiple of zero, the slope is c_{11}/c_{21}^2 and at any charge the slope is $c_{11}/(m+c_{21})^2$.

Regression analysis showed that, although all ofthe conditions investigated gave very similar charge multiple-brightness relationships, there were significant differences. In particular, regardless of charge level, high-EA pulp that had been delignified in a D_0 stage at the relatively high KF of 0.24 had higher D_1E brightness than any of the other pulps. This effect compensated somewhat for the higher (EO) kappa number of this pulp relative to that ofthe low-EA pulp delignified in a D_0 stage at the same KF. Conversely, high-EA pulp that had been delignified in a D_0 stage at the relatively low KF of 0.16 had lower D_1E brightness than any of the other pulps, adding to the disadvantage already suffered by this pulp on account of its relatively high (EO) kappa number. All of the low-EA pulps and the high-EA, 0.20 KF pulp fell on a curve intermediate between the above two cases, as shown in **Fig. 3.**

The values of c_{01}, c_{11}, and c_{21} for the high-EA, high-KF pulp are 91.32, 0.7372, and 0.04141, respectively. For the high-EA, low-KF pulp they are 90.35, 0.9669, and 0.03728; for all of the remaining pulps, they are 90.10, 0.7405, and 0.03596.

D_2 model

The D_2 stage can be accurately represented by the model used in the earlier study [5]. The relevant equation is:

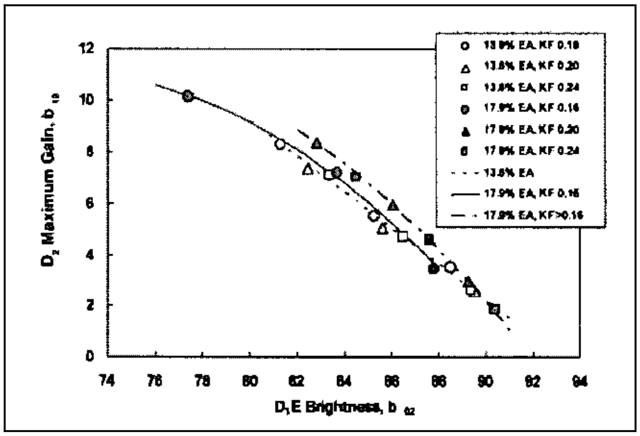
$$y_2 = b_{02} + b_{12} \cdot [1 - \exp(-b_{22} \cdot x)] \tag{4}$$

in which y_2 = brightness after the D_2 stage and χ = ClO_2 charge in the D_2 stage.

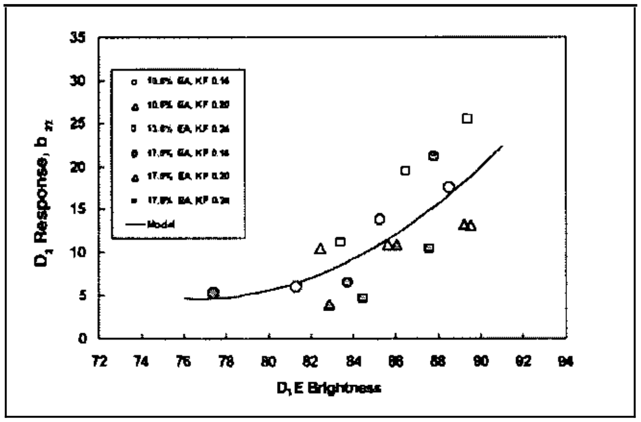
The constants b_{02}, b_{12}, and b_{22} may be interpreted as, respectively, the brightness of the pulp entering the stage, the maximum brightness gain achievable in the D_2 stage, and a constant characteristic of the relative rate of approach to this maximum as the chemical charge is increased. The D^2 stage response curve exhibits a well defined and rapidly approached brightness ceiling, given by $b_{02} + b_{12}$.

Both b_{12} and b_{22} depend on the brightness of the pulp entering the D_2 stage. Consequently the model must include mathematical descriptions of the relationships between these parameters and the entering brightness. These descriptions were obtained by regression analysis of the experimental bleaching data.

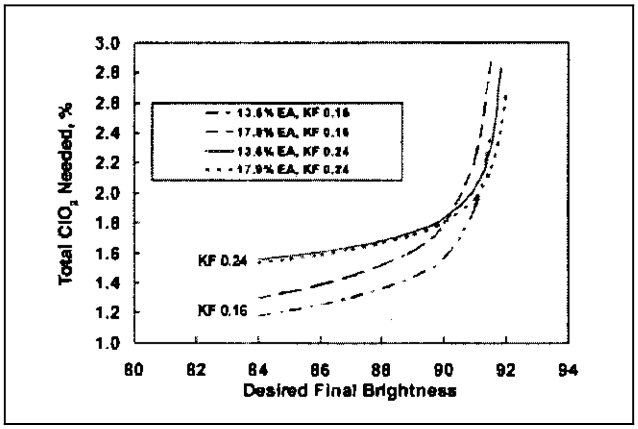
Figure 4 shows the resulting correlations between b_{12} and the entering pulp brightness. A single relationship was evident for all of the low-EA pulps, regardless of D_0 stage KF. High-EA pulps that had been through a 0.16 KF D_0 stage followed a curve very similar to that of the low-EA pulps, but



4. Maximum possible brightness gain in the D_2 stage vs. the brightness of the pulp entering the stage.



6. Dependence of the D_2 stage model parameter b_{22} on entering pulp brightness.



7. Minimum ClO_2 requirement vs. final brightness target. D(EO)DED sequence.

high-EA pulps bleached with a D_0 KF greater than 0.16 could be bleached to significantly higher brightness in the D_2 stage. This corresponded to an increase in the brightness ceiling of approximately 0.8 points.

The equations of the lines shown in Fig. 4 are of the form:

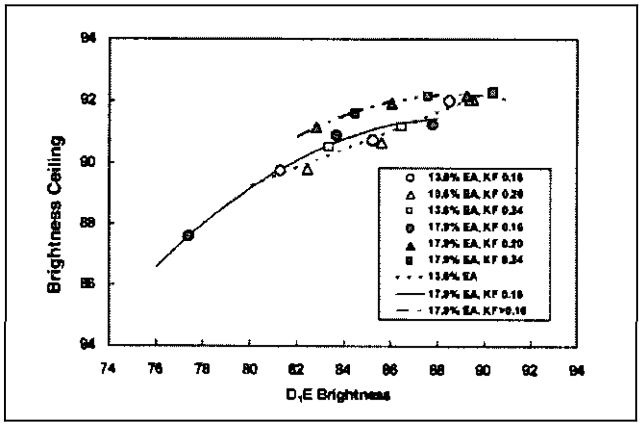
$$b_{12} = b_{120} + b_{121} \cdot y_1 - b_{122} \cdot y_1^2 \tag{5}$$

in which b_{12} = maximum possible brightness gain in the D_2 stage (a parameter in Eq. 4), y_1 = brightness after the D_1 and E stages, and b_{120}, b_{121}, and b_{122} = regression coefficients.

The values of b_{120}, b_{121}, and b_{122} for the low-EA pulps are -87.43, 2.90, and 0.0211. For the high-EA. low-KF pulp they are -142.08, 4.26, and 0.0296. For the high-EA, higher-KF pulps they are -141.33, 4.26, and 0.0296.

The brightness ceiling advantage of the high-EA, high-KF pulps is more apparent in **Fig. 5,** which shows the estimated ceiling value as a function of entering brightness for each pulp condition.

The other input required by the D_2 stage model is the parameter b_{22} of Eq. 4. It can also be predicted from the brightness of the pulp entering the stage, although with somewhat less precision than b_{12}, as shown in **Fig. 6.** This lack of precision is not serious, since the response curve is relatively insensitive to this parameter, except at unrealistically low ClO_2 charges.



5. D_2 stage brightness ceiling dependence on entering pulp brightness.

The equation of the lines shown in Fig. 6 is of the form:

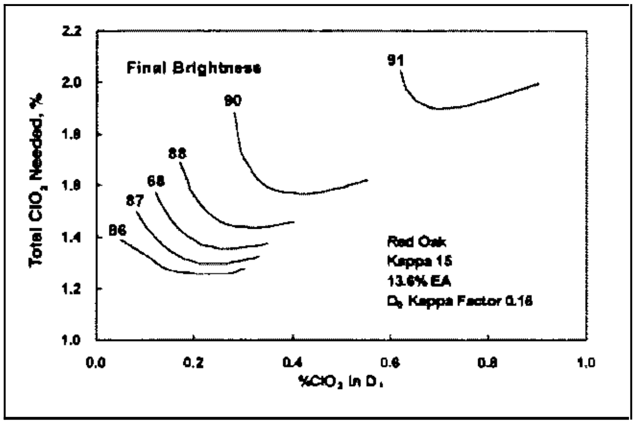
$$b_{22} = b_{220} - b_{221} \cdot y_1 + b_{222} \cdot y_1^2 \tag{6}$$

in which b_{22} = maximum possible brightness gain in the D_2 stage (a parameter in Eq. 4), y_1 = brightness after the D_1 and E stages, and b_{220}, b_{221}, and b_{222} = regression coefficients.

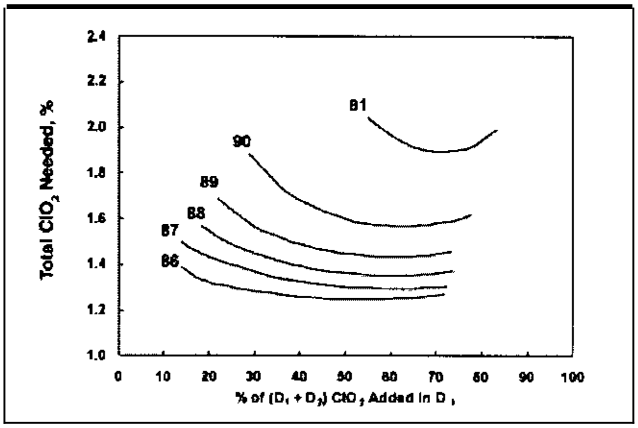
The values of b_{220}, b_{221}, and b_{222} are 504.9, 13.06, and 0.0853.

Applications of the model

A major motivation for deriving a full-sequence model of an existing bleach plant is that it provides a way to optimize bleach plant operation. Of course, optimization will only be possible with respect to the independent variables (e.g., chemical charges) included in the model. Another benefit of having such a model available is that, from a research standpoint, it allows the bleachability of a given pulp to be unambiguously characterized in terms of a curve showing the minimum chemical requirement for any desired final brightness target. Other methods, such as laboratory bleaching with constant conditions in all but the last stage and varying the chem-



8. Total C/O$_2$ requirement vs. ClO$_2$ charge in the D$_1$ stage for D$_0$ stage kappa factor 0.16.



9. Total ClO$_2$ requirement vs. relative allocation of chemical to the D$_1$ and D$_2$ stages.

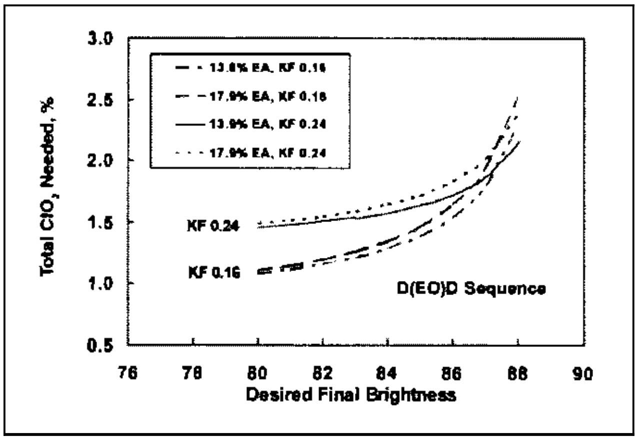
ical in that stage, fail to show each pulp to its best advantage and may well result in incorrect rankings of pulps with respect to their bleachabilities. In the following discussion we use the model derived here to illustrate both applications.

Figure 7 shows the minimum ClO$_2$ requirement to reach various final brightness targets. These curves are characteristic ofthe bleachabilities ofthe four pulp types represented. For brightness targets of 91 or lower, the most economical strategy within the range of applicability of the model for this wood furnish and unbleached kappa number is to pulp at the lower EA charge and use a D$_0$ stage KF at the low end of the range. In the 84-86 brightness range, this produces a ClO$_2$ savings of approximately 25% relative to using a KF of 0.24. Only at the extremely high brightness level of 92 is the use of both a high EA and high KF justified.

Figure 8 addresses the question of how to optimally allocate ClO$_2$ to the different D stages in the sequence. For a brightness target of 90, for example, the total ClO$_2$ requirement is minimized when the D$_1$ ClO$_2$ charge is 0.4% and the KF is 0.16. **Figure 9** presents the same information in terms of percent of the combined D$_1$ and D$_2$ charges that should he allocated to the D$_1$ stage to minimize total chemical requirement. For minimum total chemical consumption, 60%-75% of the D$_1$+D$_2$ ClO$_2$ should be added in the D$_1$ stage. The required percentage is higher when the brightness target is higher, and higher brightness targets are less forgiving of departures from the optimum allocation.

Three-stage bleaching

The model can also be used to predict the behavior of the pulps studied when the bleaching sequence has only three stages. This involves the assumption that the pulp brightness changes little during the second extraction stage, since the model is based on measurements of D$_1$E brightness, not D$_1$ brightness. Experience suggests that this assumption is valid.



10. Minimum ClO$_2$ requirement vs. final brightness target D(EO)D sequence.

Figure 10 shows the results of optimization to minimize total ClO$_2$ requirement for four combinations of digester alkali charge and D$_0$ KF. A KF at the low end of the range is optimal for all brightness targets up to 87. Pulp produced at the lower EA level is more readily bleached than high-EA pulp in this short sequence, regardless of brightness target.

CONCLUSIONS

Compared to those made with 17.9% effective alkali, kraft pulps made from red oak chips with an effective alkali charge of 13.6% are more readily delignified in the first two stages of the D$_0$(EO)D$_1$ED$_2$ bleaching sequence, but they have a lower brightness at any given D$_0$(EO) kappa number.

When bleaching hardwood kraft pulps represented by the pulps studied here, the behavior of the D$_1$ stage can be precisely modeled by an equation of the form, $y_1 = c_{01} - c_{11} / (m + c_{21})$ in which y_1 = brightness after the D$_1$ and E stages and m = D$_1$ stage ClO$_2$ charge multiple (the ClO$_2$ charge in the D$_1$ stage divided by the kappa number of the pulp entering the D$_1$ stage).

Among pulps prepared with 13.6% and 17.7% effective alkali charges and bleached at D$_0$ stage kappa factors in the range 0.16-0.24, the combination of high effective alkali and high kappa factor gave the highest D$_1$E brightness at any D$_1$ charge multiple. However, the brightness advantage was not great enough to justify the incremental cost of the kappa factor increase The combination of high effective alkali and low kappa factor gave the lowest D_1E brightness at any D_1 charge multiple. All other combinations had intermediate D_1E brightness.

The D_2 stage can be accurately represented by the model used in an earlier study The relevant equation is $y_2 = b_{02} + b_{12} \cdot [1 - \exp(-b_{22} \cdot x)]$ in which y_2 = brightness after the D_2 stage, and χ = ClO_2 charge in the D_2 stage. The constants b_{02}, b_{12}, and b_{22} may be interpreted as, respectively, the brightness of the pulp entering the stage, the maximum brightness gain achievable in the D_2 stage, and a constant characteristic of the relative rate of approach to this maximum as the chemical charge is increased. The D_2 stage response curve exhibits a well defined and rapidly approached brightness ceiling, given by $b_{02}+b_{12}$. The values of b_{12} and b_{22} are functions of the entering pulp brightness and can therefore be predicted from that brightness

The combination of high effective alkali and high D_0 kappa factor gives pulp with a higher final brightness ceiling than any other combination. However, for brightness targets of 91 or lower, the combination of low effective alkali and low kappa factor is the most economical.

For minimum total chemical consumption, 60%-75% of the D_1+D_2 ClO_2 should be added in the D_1 stage. The required percentage is higher when the brightness target is higher, and higher brightness targets are less forgiving of departures from the optimum allocation

When bleaching in the three-stage sequence $D_0(EO)D_1$, a kappa factor at the low end of the range is optimal for all brightness targets up to 87, and pulp produced at the lower effective alkali level is more readily bleached than high effective alkali pulp, regardless of brightness target. TJ

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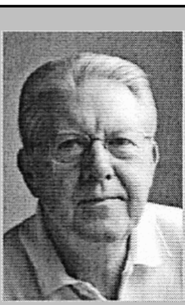
INSIGHTS FROM THE AUTHORS



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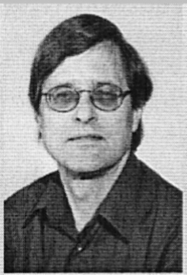

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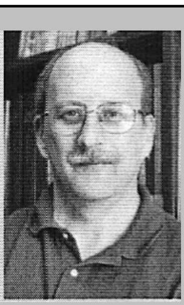

Courchene

Given a fully bleached pulp brightness target, pulp mill operators can choose from a variety of different process conditions to achieve the desired brightness. In a kraft mill with a five-stage ECF bleach plant, for example, the operator has to decide how to allocate C1O2 to the D0, D1 and D2 stages, and may also have some flexibility in the choice of digester alkali charge.

In this paper, we address the question of how to make these decisions in a way that will result in the lowest possible total C1O2 cost. In particular we advocate and illustrate a method of answering this question by means of a systematic laboratory bleaching study and suitable analysis of the results. It seems likely that many mills could achieve significant cost reductions in this way and that the cost of the laboratory study would be small in comparison to the achievable savings.

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