Using multistage models to evaluate how pulp washing after the first extraction stage impacts elemental chlorine-free bleach demand

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ABSTRACT: Steady-state models were constructed to predict the response of a southern U.S. softwood brownstock to three- and five-stage elemental chlorine-free (ECF) bleach sequences. The models provided insight into how typical (EO) washing efficiencies from a vacuum drum unit affected pulp brightening and total chlorine dioxide consumption. When (EO) carryover was between 15% and 30%, the chlorine dioxide needed to reach target brightness increased by 8% to 15% for the D_0(EO)D_1(EP)D_2 sequence (89% ISO) and by 15% to 23% for the D_0(EO)D_1 sequence (86% ISO) versus perfect washing. Use of (EO) filtrate as D_0 shower water, such as in split-flow countercurrent washing, caused the bleach uptake to increase by 1.5 to 3.0 kg chlorine dioxide (ClO_2)/ton pulp when compared to using cleaner D_0 shower water sources. The ClO_2 consumed by 15% to 30% (EO) washer carryover is comparable to that consumed by typical carryover levels from brownstock washing (~10 kg Na_2SO_4/ton pulp). High (EO) carryover made ECF bleaching to higher brightness targets more difficult.

Application: Multistage models are employed to estimate how typical levels of extraction washer carryover, as well as how extraction washer filtrate reuse in countercurrent washing, affects chlorine dioxide consumption and brightness development of a softwood kraft pulp when bleached with ECF sequences. These models could be adapted to simulate mill data, used to optimize bleaching operations, and used in process control strategies.

During kraft pulp bleaching, an appreciable level of dissolved organics and spent chemicals may be carried over from one stage into the next stage, which negatively affects overall bleach sequence performance [1-3]. Hence, interstage washing is a vital component of a bleaching stage that assures low-cost and consistent pulp bleaching. Elemental chlorine-free (ECF) technology is the dominant method used for bleached pulp production, mainly due to its ability to selectively brighten while preserving fiber strength and minimizing pulp yield losses. Several PAPTAC surveys [4-8] have been conducted to benchmark and to track best practices for ECF bleaching of softwood kraft pulps, some of which have specifically examined interstage pulp washing.

Among the interstage washing operations used in the bleach plant, it has been reported by PAPTAC surveys [7,8] that the majority of Canadian mills utilize vacuum drum units. Such washers are commonly employed in North American bleach plants, and operate with various countercurrent filtrate schemes as shower water. It is not uncommon for washer shower water to be partially supplemented with fresh hot water or white water. Drum washers often operate at 10% to 70% over their original design capacity [7]. These washing units typically remove 70% to 85% of the dissolved materials contained in the spent liquor leaving the bleaching stage [1].

Examination of the surveys revealed that the mills that had high relative bleach consumption tended to use higher D_1 multiple charges than their counterparts with relatively low bleach consumption (about 0.35% vs. 0.22% chlorine dioxide (ClO_2)/post-extraction kappa no.) [5]. Generally, D_1 brightening becomes less efficient when the D_1 multiple is higher than ~0.25 [4-6,8-10]. The analysis also noted that the high bleach usage mills added acid to the extracted pulp to control pH in the D_1 stage. A follow-up survey [8] revealed that extraction stage washers operated with a wash ratio (defined as the amount of washer shower water applied divided by the water in the discharged pulp mat) of 0.5 to 1.5. Almost two-thirds of the respondents use a wash ratio below 1.2. These observations suggest that there is appreciable carryover from extraction entering the D_1 stage, which is partially contributing to the elevated bleach consumption at the high bleach usage mills [8].

The bleaching literature contains numerous reports [11-18] on how interstage washing affects overall bleaching operations of chlorine-based bleach sequences. These earlier studies from the 1970s and 1980s focused on how to reduce the amount of fresh water consumed, waste effluent discharged, and energy consumed. However, there have been relatively few investigations that specifically examine how interstage washing affects bleach consumption for ECF sequences

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[19,20]. It is generally assumed by the industry that the conclusions drawn from the earlier literature with chlorine-based bleach sequences are directly applicable to today's ECF bleaching technology.

Yankowski [11] examined how interstage washing efficiencies affected the $CE_1D_1E_2D_2$ bleaching of a softwood pulp. The study calculated washing efficiencies based on dissolved solids measurements. It was observed that poor or no pulp washing after the D_1 stage and/or the E_2 stage had a minor effect on the overall bleach performance. When the E_1 washing decreased from 90% to 75%, the author observed that the D_1 brightness decreased by 3 points for a fixed D_1 bleach charge. MacDonald [12] quantified how E_1 carryover affected hypochlorite consumption in the $(CD)E_1H$ portion of the $(CD)E_1HD_1E_2D_2$ sequence. The washed E_1 pulp entering the H stage contained 1.5 to 4.4 kg dissolved lignin/ton pulp when the lignin was expressed as equivalent sodium. When the E_1 carryover was reduced from the high to the low value, the amount of hypochlorite needed decreased by 8.2 kg NaOCl/ton pulp.

Histed and co-workers [1,2,13-17] published numerous studies in the 1970s examining how direct countercurrent recycling of washer filtrates affected the bleaching of Canadian softwood kraft pulps. In one study [13], a 30-kappa brownstock was bleached to 92% Elrephro (about 89.5% ISO) using the $(D+C)E_1D_1E_2D_2$ sequence that employed 70% chlorine dioxide substitution. It was noted that the D_1 brightness decreased by almost 8 points and that the D_2 brightness decreased by 2 points when compared to no filtrate recycle. This loss was recovered when the D_1 charge was increased from 1.45% to 1.75% ClO_2. In a similar study [15], a 24-kappa brownstock was bleached with the same sequence. When filtrate recycle was employed, it was necessary to increase the (D+C) kappa factor from 0.21 to 0.24 and boost the D_1 charge from 1.42% to 1.52% ClO_2 to reach the brightness target. In a third study [17], Histed and co-workers examined how different interstage wash ratio values affected bleach consumption of the $(C+D)E_1HD_1E_2D_2$ sequence. There was little impact on hypochlorite or chlorine dioxide consumption when the wash ratios at H, D_1, and E_2 washers were decreased from 1.3 to 0.5. Lowering the wash ratio at the E_1 washer from 1.3 to 1.0 considerably increased the hypochlorite uptake in the H stage by ~10.6 kg NaOCl/ton pulp.

Waritovaara [18] explored how different filtrate recycle schemes affected the bleach consumption of a 28-kappa pine kraft pulp with the $(D/C)E_1D_1E_2D_2$ sequence. A 30% chlorine dioxide substitution level was used in the (D/C) while a wash ratio of ~1.55 was applied to each washer. The washed pulp was discharged at ~15% consistency. Direct countercurrent washing required 11% more bleach to reach 89% ISO brightness vs. not washing the pulp with recycled filtrates. Other countercurrent washing schemes, such as jump-stage countercurrent or split-flow countercurrent, had similar bleach consumptions as open interstage washing. The high wash ratio and discharge consistency ensured that there was low E_1 carryover. The higher oxidant chemical usage with direct countercurrent washing was attributed to E_1 filtrate breaking through the pulp mat at the (D/C) washer, which mixed with (D/C) seal tank filtrate and carried backwards to the brownstock dilution water of the (D/C) stage [1-3,16]. The E_1 dissolved organics consume a portion of the oxidants applied in (D/C) stage similar to black liquor carryover.

Some contemporary studies [19,20] examined direct countercurrent washing with the $D_0(EOP)D_1$ sequence. These researchers observed an increase in chlorine dioxide demand from 0% to 0.3% (on pulp) when using (EOP) filtrate to wash the D_0 pulp versus using D_1 filtrate. In another recent report, Frigieri et al. [21] examined different interstage wash ratios of 1 to 0 with a jump-stage countercurrent recycle with the $D_0(EP)D_1P$ sequence. The authors disclosed that final brightness of the oxygen-delignified eucalypt pulp declined from 92% ISO to 88% ISO when the wash ratio decreased from 1 to 0.3 while the oxidant charges in each stage were invariant.

It is apparent that first extraction stage carryover, apart from black liquor or post-oxygen carryover, can appreciably contribute to the oxidant bleach load when using chlorine-based bleach sequences, and, in particular, when extraction filtrate is reused as the shower water in the preceding washer. Nevertheless, relatively few publications have re-examined how the first extraction washer efficiency affects total bleach usage with ECF-based bleach sequence. Furthermore, most mills do not monitor interstage carryover [7,9,10,22]. It is difficult to quantify bleach washer efficiency using a simple and quick test method such as is done with brownstock washing [22]. Recently, efforts in this area [8-10,23] have related extraction carryover into the D_1 stage by using the kappa number test. The kappa number contributions from well-washed extracted pulps and their dissolved organic carryover can be correlated to the brightening response in the D_1 stage [23].

The current investigation reports the findings obtained from the spreadsheet modeling of ECF bleach sequences to determine how first extraction stage washing efficiency and filtrate reuse affects total chlorine dioxide consumption for ECF sequences. The models can predict the bleaching response after $D_0(EO)$, D_1 and D_2, and have been previously discussed [23-25]. The $D_0(EO)$ and D_1 units have the capacity to consider washer carryover entering that stage. The inputs and outputs for each unit (e.g., kappa number and/or brightness of the pulp) are coupled to each other using an analogous approach that has been reported by earlier investigators [26,27].

METHODOLOGY

Steady-state simulations of $D_0(EO)D_1(EP)D_2$ and $D_0(EO)D_1$ sequences were conducted using a hypothetical southern U.S. softwood brownstock that had a kappa number of 24 and a brightness of 23% ISO. Data from the Basta and co-workers study [28], as well as data analysis from another investigation [29], were used to calibrate the equation parameters for $D_0(EO)$ delignification, and D_1 brightening and D_2 brightening models. General conditions examined are presented in

Stage Conditions	D_0	(EO)	D_1	(EP)	D_2
Consistency, %	3.5	10	10	10	10
Temperature, °C	50	70 or 90	70	70	70
Time, min	30 – 60	60	variable	60	variable
ClO_2, % on pulp	1.00 – 3.10 (0.11 to 0.34 KF)	–	0.30 – 1.75	–	0.25
O_2, % on pulp	–	0.50 (at 0.22 MPa)	–	–	–
H_2O_2, % on pulp	–	–	–	0.20	–
NaOH, % on pulp	–	0.4·(KF)·(Kappa no.)	variable	0.50	variable
H_2SO_4, % on pulp	0.6%	–	variable	–	variable
End pH	~3	~10.5 to 11.0	~3	~11	~4
ClO_2 = chlorine dioxide; O_2 = oxygen; H_2O_2 = hydrogen peroxide; NaOH = sodium hydroxide; H_2SO_4 = sulfuric acid; and KF = kappa factor.					

I. Conditions used in the model simulations of three- and five-stage elemental chlorine-free (ECF) bleach sequences for a 24-kappa softwood brownstock to reach 84% to 89% ISO and 85% to 90% ISO, respectively.

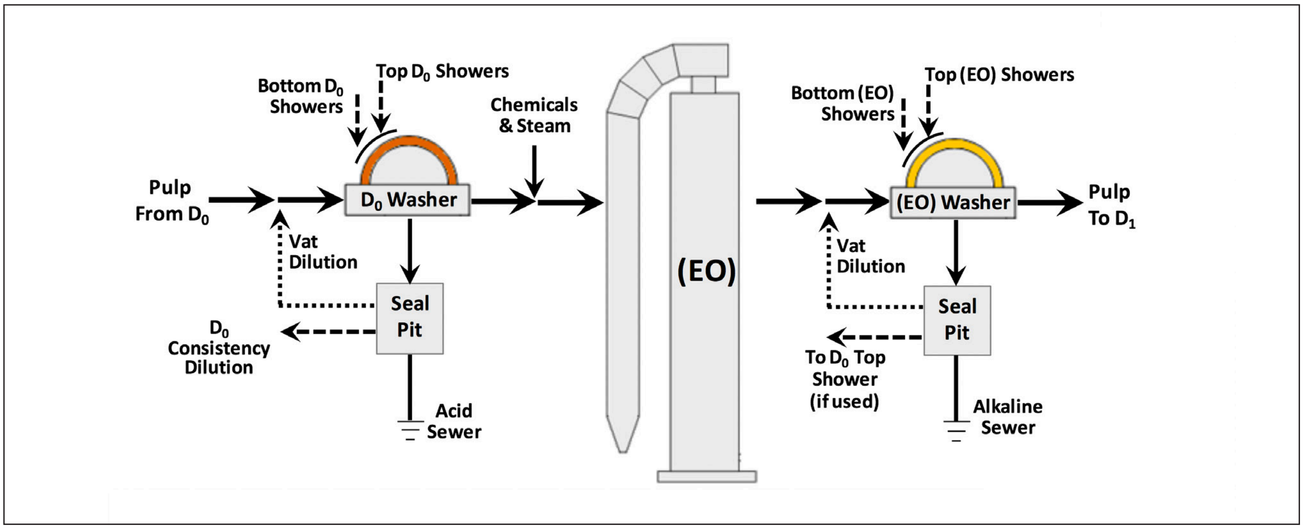
Stage	Equation	No.	Comments
D_0	D_0 Kappa $=20.6-5.14 \cdot x_0$	(1)	Based on Basta et al. data [28]; x_0 is % ClO_2 on pulp in D_0
(EO)	(EO) Kappa $= \dfrac{24}{\left(\frac{x_0 - 0.03 \cdot C_{BSW}}{2A} + 1\right)^2}$	(2)	CBSW is brownstock washer carryover (kg Na_2SO_4/ton pulp); A = 0.820 (70°C) or 0.588 (90°C)
	(EO) Brightness = B_{EO} $=63.6-3.28 \cdot$((EO) Kappa)	(3)	Based on Basta et al. data [28]
D_1	D_1 Brightness $= B_{D1} = 92 - \dfrac{\beta_1}{x_1 + \frac{\beta_1}{92 - B_{EO}}}$	(4)	x_1 is % ClO_2 on pulp in D_1;
	$\beta_1 = 4.54 \cdot$(Washed Kappa)-7.43	(5)	
	Washed Kappa = (EO) Pulp Kappa + (EO) Carryover Kappa	(6)	(EO) Carryover Kappa is expressed as kappa units (on pulp) [23]
(EP)	(EP) Brightness $= B_{EP} = 0.765 \cdot B_{D1} + 21.8$	(7)	Based on Basta et al. data [28] for a fixed 0.20% peroxide charge
D_2	D_2 Brightness $= B_{D2} = 92 - \dfrac{\beta_2}{x_2 + \frac{\beta_2}{92 - B_{EP}}}$	(8)	x_2 is % ClO_2 on pulp in D_2;
	$\beta_2 = 0.250 \cdot B_{EP} + 23.0$	(9)	Based on D_2 model [25] tuned to Basta et al. data [28]

II. Steady-state equations for the individual stages of the ECF sequences for bleaching 24-kappa brownstock.

Table I. The conditions from the laboratory study [29] are relatively consistent with current bleaching practices with North American bleach plants [4-6].

The empirical expressions for each of the bleach stages (Eqs. 1 to 9) are listed in Table II. Several relationships, such as Eqs. 1, 3 and 7, are derived from laboratory data [28]. It is presumed that the asymptotic brightness for the softwood kraft brownstock is around 92% ISO, which is based on the limiting light absorption and light scattering coefficients [25]. Unless otherwise specified, simulations were run assuming that there was negligible brownstock washer carryover into D_0 ($C_{BSW} \approx 0$ kg Na_2SO_4/ton pulp). The D_0(EO)D_1(EP)D_2 sequence utilized a milder (EO) stage at 70°C, whereas the D_0(EO)D_1 sequence used an aggressive (EO) stage at 90°C to attain 85% to 89% ISO more easily with fewer bleaching stages.

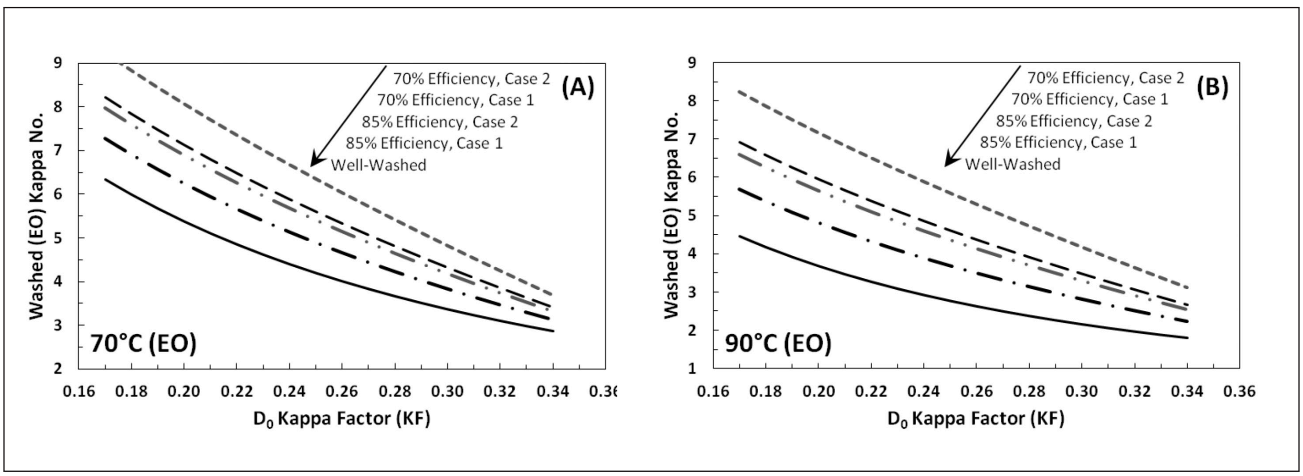
Extraction carryover was expressed in terms of kappa units on pulp [23]. This quantity is represented as the difference between the kappa number of the discharged pulp from the (EO) washer, which included its filtrate, and the kappa number of the well-washed (EO) pulp without filtrate [8,9,23].



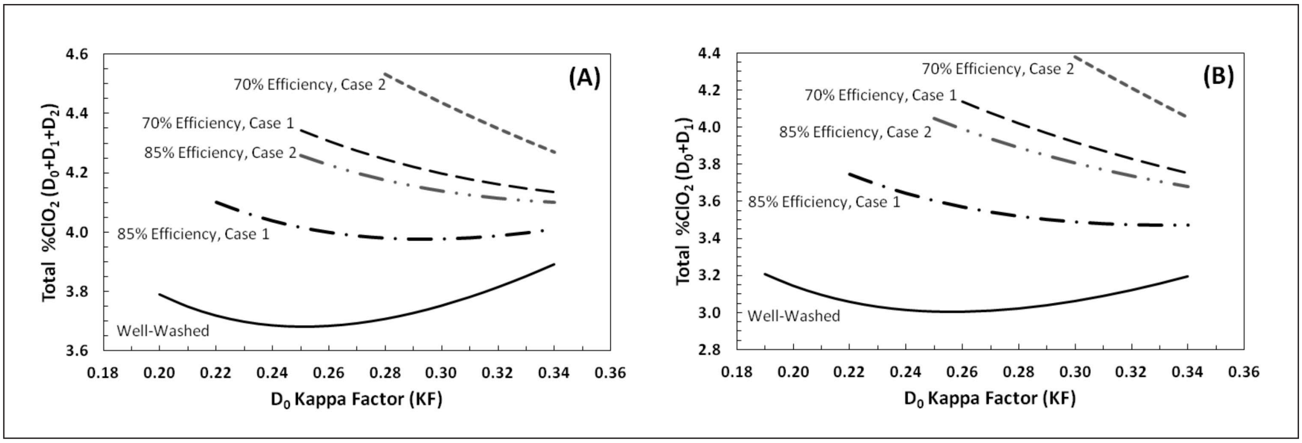
1. General water and pulp stream flows of the D_0 washer, (EO) stage, and (EO) washer.

Washing efficiencies of 85% to 70% with the (EO) washer were examined and compared to a well-washed pulp with no carryover (i.e., Control). These efficiency levels were chosen to be a representative range for vacuum drum washers [30-32], which correspond to 15% to 30% carryover, respectively. Extraction carryover was calculated from the total amount of dissolved (EO) material, expressed as kappa units (on pulp), exiting the stage but prior to washer vat dilution. The total is determined from what is generated in the (EO) stage (i.e., Eq. 1 minus Eq. 2), plus what is recycled back from the (EO) seal tank, if this filtrate is used as shower water at the D_0 washer [3]. For the simulations where (EO) filtrate is used, only one-half of the total D_0 shower water was supplemented by this source. In this split-flow arraignment, the (EO) filtrate was applied at the top D_0 shower bars to ensure that none of it broke through the pulp mat and entered into the D_0 seal tank [1-3,17]. It was assumed that any other recycled filtrates used as shower water, such as from D_1, (EP) and D_2 seal tanks, which might be used at D_0 and (EO) washers, contained dissolved substances that do not contribute to ClO_2 consumption (i.e., 0 kappa units) [1,11,17]. In addition, it was further presumed that nominal D_0 washer carryover has an insignificant effect on the total ClO_2 bleach load [33-35]. Simulations were performed using a 1.16 wash ratio, a 1.5% washer vat consistency, and a 12% discharged mat consistency.

The equations listed in Table II were run from a spreadsheet software program (Excel, version 2016; Microsoft Corp., Redmond, WA, USA), along with the material balances for the washers around the (EO) stage [3]. A solver routine in the software was used to minimize the total overall chlorine dioxide charge for a targeted brightness value and a given (EO) washer efficiency. An iterative calculation mode was used to solve material balances, which had nested recycle loops that simulate partial countercurrent washing. Iterative calculations were executed by the spreadsheet program until differences between successive computations were less than 0.01%.



2. Effect of (EO) washer efficiency and D_0 kappa factor charge on washed (EO) kappa number for the bleaching delignification: (A) D_0(EO)D_1(EP)D_2 with 70°C (EO), and (B) D_0(EO)D_1 with 90°C (EO). Case 1 refers to D_0 washer using shower water from cleaner sources, and Case 2 refers to (EO) filtrate being at the top shower bars of D_0 washer. Well-washed (i.e., Control) refers to 100% washing efficiency.



3. Effect of (EO) washer efficiency and D_0 kappa factor on the total chlorine dioxide bleach demand when bleaching with: (A) D_0(EO)D_1(EP)D_2 to 89% ISO, and (B) D_0(EO)D_1 to 86% ISO. Designations for the various cases are the same as those listed in Fig. 2.

RESULTS

Several scenarios have been examined to determine how (EO) carryover affects chlorine dioxide consumption for D_0(EO)D_1(EP)D_2 and D_0(EO)D_1 sequences. The well-washed pulp scenario assumes that there is 0% washer carryover (i.e., 100% washing efficiency). Case 1 presumes that the D_0 washer uses shower water that is relatively clean and that is free of (EO) dissolved solids (Fig. 1). The bottom D_0 showers may use hot water, white water, or D_1 filtrate, whereas the top D_0 showers may use D_1 filtrate or (EP) filtrate (if available) [7]. The bottom (EO) showers may use hot water, (EP) filtrate (if available), or D_1 filtrate; the top (EO) showers may use hot water or D_1 filtrate [7,8]. Case 2 is similar to Case 1 with one difference. In Case 2, (EO) filtrate is recycled to the top shower bars of D_0 washer; one-half of the applied shower water is (EO) filtrate [1,2,7,8,36]. The amount of (EO) dissolved solids increases in the (EO) stage. In Case 1 and Case 2, the dissolved solids in the shower water sources (other than the (EO) filtrate) are assumed to have negligible chlorine dioxide bleach consumption in the subsequent stage. The results from the spreadsheet calculations based on these scenarios are presented.

Figure 2 illustrates how the washed kappa number of the D_0(EO) pulp varies with the D_0 kappa factor (KF) charge and (EO) washer efficiency for the two cases versus the Control. If the brightness target of the D_0(EO)D_1(EP)D_2 sequence is 89% ISO, then the extracted pulp needs to have a washed D_0(EO) kappa that is between 3.8 and 4.6. This target shifts to 2.4 to 3.1 when bleaching to 86% ISO with the D_0(EO)D_1. The bleach necessary to attain these delignification targets corresponds to 0.23 to 0.27 KF (2.1% to 2.5% ClO_2 on pulp) for the Control. Depending upon the washing efficiency and washing scheme employed (Case 1 or Case 2), the incremental increase in the D_0 charge ranged from 0.04 to 0.09 KF (0.36 to 1.00% ClO_2 on pulp). The amount of carryover in the washed D_0(EO) pulps ranged from 0.4 to 0.6 kappa units when bleaching with a D_0(EO)D_1(EP)D_2 sequence to 89% ISO, and from 0.4 to 1.3 when bleaching with a D_0(EO)D_1 sequence to 86% ISO.

Figure 3 plots the total amount of ClO_2 consumed vs. the D_0 charge when bleaching to 89% ISO with the D_0(EO)D_1(EP)D_2 sequence and to 86% ISO with the D_0(EO)D_1 sequence. The minimized ClO_2 demand for the Control was approximately 36.8 kg ClO_2/ton for the five-stage sequence and approximately 30.0 kg ClO_2/ton for the three-stage sequence. Table III presents how (EO) washing efficiency and (EO) filtrate reuse affected pulp brightness when the chlorine dioxide charges are fixed at the Control levels. The D_2 brightness dropped by 0.7 to 1.4 points with the D_0(EO)D_1(EP)D_2 sequence as washing efficiency decreased with Case 1. These losses doubled when (EO) filtrate was used in a split-flow arrangement (Case 2). D_1 brightness losses for the three- and five-stage sequences ranged from 1.6 to 7.2 points. Table IV indicates how much chlorine dioxide bleach is needed in D_1 to recover the brightness losses while the chlorine dioxide charges in D_0 and D_2 (if used) remained fixed. The increase in D_1 bleach demand ranged from 3.5 to 10.5 kg ClO_2/ton to counteract the 0.7 to 1.6 kappa units of (EO) carryover.

Table V shows the minimized chlorine dioxide demand for D_0(EO)D_1(EP)D_2 and D_0(EO)D_1 at different washing efficiencies for Case 1 and 2. Balancing the ClO_2 used at D_0 and D_1 stages can afford some total bleach savings. For Case 1 where the (EO) washer is operating at 85% efficiency, the total amount of bleach saved was small (0.4 to 1.1 kg ClO_2/ton). There was an advantage of rebalancing the ClO_2 charges at D_0 and D_1 when (EO) washer efficiency was lower than 85% for Case 1, or when (EO) filtrate is recycled as D_0 shower water (Case 2). In these circumstances, the amount of chlorine dioxide saved ranged from 1.4 to 3.5 kg /ton pulp when rebalancing the bleach charges.

Figure 4 illustrates how washing efficiency and (EO) filtrate usage affected total ClO_2 needed to reach 85% to 90% ISO with the D_0(EO)D_1(EP)D_2 sequence and 84% to 89% ISO brightness with the D_0(EO)D_1 sequence. Similar bleach consumption trends were observed for these ranges as has been presented for 89% ISO and for 86% ISO scenarios.

$D_0(EO)D_1(EP)D_2$					
(EO) Washing Efficiency	(EO) Filtrate Used at D_0 Washer	D_0(EO) Washed Kappa No.	(EO) Carryover (Kappa units)	D_1 Brightness (% ISO)	D_2 Brightness (% ISO)
Well-Washed (Control)	No	4.2	0	83.9	89.0
85% Efficiency (Case 1)	No	4.9	0.7	82.3	88.3
70% Efficiency (Case 1)	No	5.6	1.4	80.3	87.6
85% Efficiency (Case 2)	Yes	5.4	1.2	80.7	87.8
70% Efficiency (Case 2)	Yes	6.3	2.1	78.5	86.9
$D_0(EO)D_1$					
(EO) Washing Efficiency	(EO) Filtrate Used at D_0 Washer	D_0(EO) Washed Kappa No.	(EO) Carryover (Kappa units)	D_1 Brightness (% ISO)	
Well-Washed (Control)	No	2.7	0	86.0	
85% Efficiency (Case 1)	No	3.6	0.9	82.1	
70% Efficiency (Case 1)	No	4.5	1.8	78.8	
85% Efficiency (Case 2)	Yes	4.3	1.6	79.6	

III. Influence of (EO) washer efficiency and (EO) filtrate reuse with $D_0(EO)D_1(EP)D_2$ and $D_0(EO)D_1$ sequences. Chlorine dioxide charges used in the D-stages were fixed at the levels for the well-washed pulp (Control): 2.29% D_0 (0.251 KF), 1.14% D_1 and 0.25% D_2 for $D_0(EO)D_1(EP)D_2$; and 2.32% D_0 (0.254 KF) and 0.68% D_1 for $D_0(EO)D_1$.

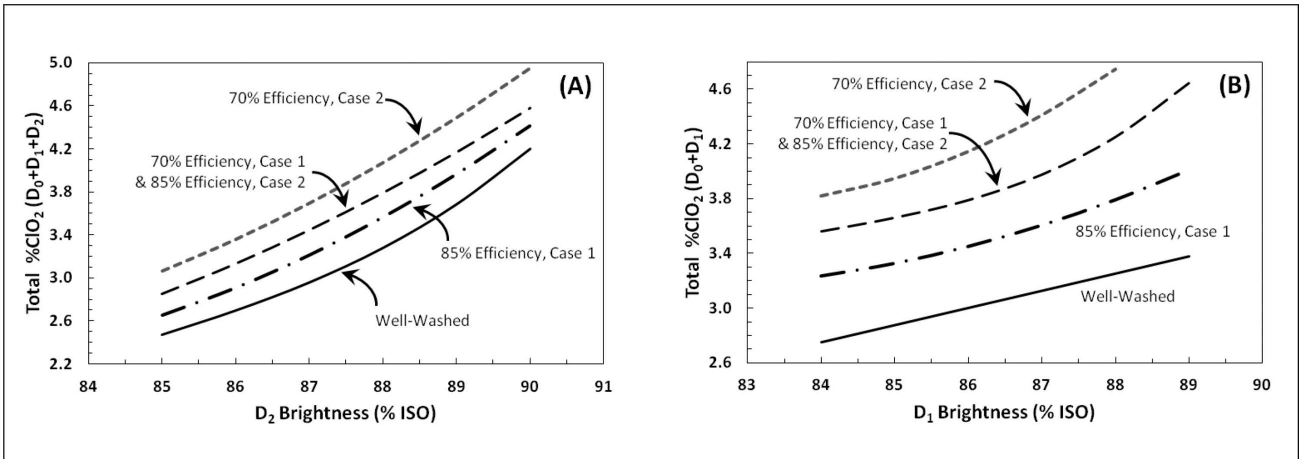
$D_0(EO)D_1(EP)D_2$					
(EO) Washing Efficiency	(EO) Filtrate Used at D_0 Washer	D_0(EO) Washed Kappa No.	(EO) Carryover (Kappa units)	D_1 ClO_2 to Reach 83.9% ISO	Total ClO_2 Used
Well-Washed (Control)	No	4.2	0	1.14%	3.68%
85% Efficiency (Case 1)	No	4.9	0.7	1.49%	4.03%
70% Efficiency (Case 1)	No	5.6	1.4	> 1.75%	> 4.30%
85% Efficiency (Case 2)	Yes	5.4	1.2	1.74%	4.28%
70% Efficiency (Case 2)	Yes	6.3	2.1	> 1.75%	> 4.30%
$D_0(EO)D_1$					
(EO) Washing Efficiency	(EO) Filtrate Used at D_0 Washer	D_0(EO) Washed Kappa No.	(EO) Carryover (Kappa units)	D_1 ClO_2 to Reach 86.0% ISO	Total ClO_2 Used
Well-Washed (Control)	No	2.7	0	0.67%	3.00%
85% Efficiency (Case 1)	No	3.6	0.9	1.26%	3.59%
70% Efficiency (Case 1)	No	4.5	1.8	> 1.75%	> 4.08%
85% Efficiency (Case 2)	Yes	4.3	1.6	1.72%	4.05%

IV. Influence of (EO) washer efficiency and (EO) filtrate reuse on chlorine dioxide (ClO_2) usage at the D_1 stage when bleaching to 89% ISO with $D_0(EO)D_1(EP)D_2$, and to 86% ISO with $D_0(EO)D_1$. Chlorine dioxide used in the D_0 and D_2 (if used) was fixed at the levels for the well-washed pulp (Table III). Well-washed indicates no (EO) washer carryover (i.e., 100% washing efficiency).

$D_0(EO)D_1(EP)D_2$					
(EO) Washing Efficiency	(EO) Filtrate Used at D_0 Washer	D_0(EO) Washed Kappa No.	(EO) Carryover (Kappa units)	D_1 ClO_2	Total ClO_2 Used
Well-Washed (Control)	No	3.8 to 4.6	0	0.98% to1.35%	3.68%
85% Efficiency (Case 1)	No	3.5 to 4.4	0.4 to 0.6	0.89% to 1.23%	3.99%
70% Efficiency (Case 1)	No	3.4 to 3.6	0.5 to 0.6	0.78% to 0.89%	4.14%
85% Efficiency (Case 2)	Yes	3.3 to 3.7	0.5 to 0.6	0.75% to 0.95%	4.14%
70% Efficiency (Case 2)	Yes	3.7	0.8	0.92%	4.27%

$D_0(EO)D_1$					
(EO) Washing Efficiency	(EO) Filtrate Used at D_0 Washer	D_0(EO) Washed Kappa No.	(EO) Carryover (Kappa units)	D_1 ClO_2	Total ClO_2 Used
Well-Washed (Control)	No	2.4 to 3.1	0	0.47% to 0.93%	3.01%
85% Efficiency (Case 1)	No	2.2 to 2.8	0.4 to 0.8	0.37% to 0.75%	3.48%
70% Efficiency (Case 1)	No	2.7 to 2.9	0.8 to 1.0	0.65% to 0.78%	3.77%
85% Efficiency (Case 2)	Yes	2.6 to 2.7	0.7 to 0.8	0.58% to 0.69%	3.70%

V. Influence of (EO) washer efficiency and (EO) filtrate reuse on the total chlorine dioxide usage when bleaching to 89% ISO with $D_0(EO)D_1(EP)D_2$, and to 86% ISO with $D_0(EO)D_1$. The amount of ClO_2 used in the D_0 and D_1 were allowed to vary; 0.25% ClO_2 was used in the D_2 stage.



4. Effect of (EO) washer efficiency on the minimized chlorine dioxide demand needed to reach a given brightness target when bleaching with: (A) $D_0(EO)D_1(EP)D_2$ and (B) $D_0(EO)D_1$. Designations for the various cases are the same as those listed in Fig. 2.

DISCUSSION

The results from the multistage modeling provided insights on how (EO) carryover and (EO) filtrate reuse affected ECF bleaching. Brightness losses observed from D_2 stages (Table III) seemed to concur with earlier observations for chlorine-based bleach sequences at typical interstage washing efficiencies [13-17]. Predicted D_1 brightness losses with the simulations ranged from 1.6 to 7 points when no adjustments were made for the (EO) carryover load. These predictions agree with earlier investigations [1,34,37], which generally reported a brightness drop of 0.5 to 8 points.

The washed (EO) pulps in Fig. 3 contained from 0.3 to 2.2 kappa units of (EO) carryover, depending upon the D_0 KF used, the temperature of (EO) stage, the efficiency of the (EO) drum washer, and the reuse of (EO) filtrate as shower water. Each kappa unit of (EO) carryover into the D_1 stage resulted in an additional 4.7 kg ClO_2/ton being consumed when bleaching to 89% ISO with a $D_0(EO)D_1(EP)D_2$ sequence, and an additional 6.6 kg ClO_2/ton when bleaching to 86% ISO with a D_0(EO)D_1 sequence. In these two examples, the minimum ClO_2 demand was typically observed when the D_0(EO) pulp had a washed kappa number between 3.8 and 4.6 for the five-stage sequence, and between 2.4 and 3.1 for the three-stage sequence. Using a higher D_0 bleach charge lowers the amount of (EO) carryover entering the D_1 for a given (EO) washer efficiency. This was due to more bleaching delignification occurring at the D_0 stage with the higher KF charges vs. the delignification occurring at the (EO) stage.

The model indicated that imperfect washing after the (EO) resulted in an additional 3 to 8 kg ClO_2/ton being expended versus perfect washing (i.e., Control). This represented an 8% to 15% increase of the total bleach needed to bleach to 89% ISO with the D_0(EO)D_1(EP)D_2 sequence and a 15% to 23% increase to bleach to 86% ISO with the D_0(EO)D_1 sequence. The amount of ClO_2 consumed by (EO) carryover is somewhat similar to the amount of bleach that is consumed by brownstock washing carryover (~10 kg Na_2SO_4/ton [4-6,24]) in the D_0 stage, which is ~3 kg ClO_2/ton.

Countercurrent usage of (EO) filtrate caused the amount of dissolved organic substances in the (EO) stage, as expressed in kappa units, to rise (Fig. 2). In Case 2 where the efficiency at the (EO) washer is 85% (i.e., 15% carryover), the reuse of (EO) filtrate caused the total bleach demand to approach that of Case 1 where the washer is operating at 70% efficiency and uses cleaner D_0 shower water sources. Case 2 resulted in an increase in the chlorine dioxide demand of 1.5 to 3.0 kg ClO_2/ton versus Case 1. Hence, recycling (EO) filtrate as shower water can result in appreciably higher chlorine dioxide consumption unless washing efficiencies after the (EO) stage are sufficiently high (≥85%), especially for short ECF bleach sequences. Similar observations have been reported by Histed et al. [1] for chlorine-based bleach sequences. These authors suggested using two washing units in series after the extraction stage to achieve >95% washing efficiency when recycling extraction filtrates. Such a countercurrent washing arraignment has been used at a softwood mill bleaching with the D_0(EOP)D_1 sequence that results in very low (EOP) carryover [20].

The spreadsheet simulations also illustrated how washing efficiency and countercurrent filtrate usage affected bleach consumption for various brightness targets using three- and five-stage ECF bleach sequences (Fig. 4). The bleach uptakes from 15% and 30% (EO) carryover at other brightness targets were somewhat similar to the base cases examined in greater detail (Fig. 3). Lower (EO) washing efficiencies and reuse of (EO) filtrate made it technically more difficult to attain the upper brightness targets of >87% ISO with D_0(EOP)D_1 sequence and >89% with D_0(EO)D_1(EP)D_2 sequence.

The spreadsheet models of ECF bleaching sequences, such as the one used in this study, have the potential to be used in conjunction with other computer models reported in the literature [1,36,38,39]. Combinations of such models could provide additional insights as to how various water reduction strategies in the bleach plant can affect interstage washing efficiencies, brightness targets and chemical usage, buildup of non-process elements and dissolved solids, potential scale formation, and discharged effluent properties.

CONCLUSIONS

Computer spreadsheet models were developed to forecast the response of a 24-kappa softwood kraft brownstock when subjected to D_0(EO)D_1 and D_0(EO)D_1(EP)D_2 bleach sequences. The models examined how (EO) washing efficiencies and how (EO) filtrate reuse affected the ClO_2 consumed to attain specific brightness targets. When the (EO) carryover was increased by 0.4 to 0.8 kappa units (on pulp), the chlorine dioxide demand of the D_0(EO)D_1(EP)D_2 sequence increased by 3 to 6 kg ClO_2/ton when bleaching to 89% ISO; when the (EO) carryover was increased by 0.4 to 1.0 kappa units, the chlorine dioxide demand of the D_0(EO)D_1 sequence increased by 5 to 8 kg ClO_2/ton when bleaching to 86% ISO. Bleach savings were observed when rebalancing the chlorine dioxide charge between D_0 and D_1 when the (EO) washing efficiency was <85%, or when (EO) filtrate is re-used as D_0 shower water. Employing split-flow washing with (EO) filtrate, in combination with 70% to 85% (EO) washing efficiency, resulted in an extra chlorine dioxide uptake of 1.5 to 3.0 kg/ton pulp versus when using cleaner shower water at the D_0 washer. It was more difficult to bleach to >89% ISO with the D_0(EO)D_1(EP)D_2 sequence and to >87% ISO with the D_0(EO)D_1 sequence when (EO) carryover was present at moderate levels (i.e., 15%). Hence, the advantages of split-flow countercurrent washing with (EO) filtrate, such as reduced steam and caustic usage at (EO) stage, needs to be balanced with the noted disadvantages when optimizing bleach plant operations. **TJ**

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LITERATURE CITED

1. Histed, J., McCubbin, N., and Gleadow, P.L., in *Pulp Bleaching—Principles and Practice* (C.W. Dence and D.W. Reeve, Eds.), TAPPI Press, Atlanta, GA, USA, 1996, pp. 647-673.
2. Histed, J.A. and Nelson, G.G., in *The Bleaching of Pulp* (R.P. Singh, Ed.), TAPPI Press, Atlanta, 1979, pp. 393-411.
3. Pryke, D.W., "Water reuse in the bleach plant," *1985 Bleach Plant Operations Seminar*, TAPPI Press, Atlanta, 1985, pp. 105-113.
4. Pryke, D.C. and Reeve, D.W., *TAPPI J.* 80(5): 153(1997).

5. Pryke, D.C. and Earl, P.F., "Softwood bleaching practices in Canada: Analysis of the 2003 PAPTAC Bleaching Committee 'best practices' survey," *TAPPI Eng., Pulping, Environ. Conf.*, TAPPI Press, Atlanta, 2005.

6. Pryke, D.C., Kanters, C.J., and Tam, T., "ECF bleaching practices in Canada, Part 2: Analysis of PAPTAC Bleaching Committee survey for softwood kraft pulps," *Int. Pulp Bleaching Conf.*, PAPTAC, Montréal, 2000.

7. Towers, M. and Turner, P.A., "Survey of bleach plant washing practices in Canadian Mills," *Pulp Washing '96*, CPPA/TAPPI, Montreal/Atlanta, 1996, pp. 23-29.

8. Earl, P.F. and Schofield, M., "Pulp washing after the first extraction stage: A survey of Canadian mills," *PAPTAC Annu. Meet., 93rd*, Montréal, 2007.

9. Pryke, D.W. and Nylen, K., *Pulp Pap. Can.* 109(1): 43(2008).

10. Steelreath, E., Earl, P.F., and Vanderheide, J., "Bleach plant optimization at the Resolute Forest Products Coosa Pines mill," *TAPPI PEERS Conf.*, TAPPI Press, Atlanta, 2014.

11. Yankowski, A.A., *Tappi* 55(6): 937(1972).

12. MacDonald, G.L.W., *Pulp Pap. Mag. Can.* 73(3): 56(1972).

13. Histed, J.A. and Nicolle, F.M.A., *Pulp Pap. Mag. Can.* 75(5): T171(1973).

14. Histed, J.A. and Nicolle, F.M.A., *Pulp Pap. Mag. Can.* 74(12): T386(1973).

15. Nicolle, F.M.A and Histed, J.A., *Pulp Pap. Can.* 76(9): T253(1975).

16. Histed, J.A. and Nicolle, F.M.A., *Tappi* 59(3): 75(1976).

17. Histed, J.A. and André, G., *Pulp Pap. Can.* 78(3): TR23(1977).

18. Wartiovaara, I., *Pap. Puu* 82(5): 319(1980).

19. Maples, G.E., Ambady, R., Caron, J.R., et al., *Tappi J.* 77(11): 71(1994).

20. Vega Canovas, R. and Maples, G., *Pulp Pap.* 69(3): 83(1995).

21. Frigieri, T.C., Ventorim, G., Savi, A.F., et al., *Environ. Technol.* 36(5): 638(2015).

22. Lunn, R., *Pulp Pap. Can.* 102(3): 46(2001).

23. Brogdon, B.N., *TAPPI J.* 15(3): 178(2016).

24. Brogdon, B.N., *TAPPI J.* 14(2): 93(2015).

25. Brogdon, B.N., *TAPPI J.* 13(3): 17(2014).

26. McDonough, T.J., Rawat, N., and Krishnagopalan, G.A., *Appita J.* 57(5): 381(2004).

27. Hart, P.W. and Connell, D., *TAPPI J.* 5(4): 23(2006).

ABOUT THE AUTHORS

This article is a continuation of the spreadsheet modeling work for ECF beaching that was previously published in *TAPPI Journal* [23-25]. In this paper, we investigate how interstage washing, particularly after the first caustic extraction stage, affects oxidant consumption and brightening during the bleaching of a softwood pulp. This topic is of interest since most North American bleach plants are utilizing older washing devices that are overloaded and washing less efficiently. The extra bleaching costs incurred by poor interstage washing are not widely known.

Much has been published about countercurrent washing schemes to minimize water usage, especially with regards to how to mitigate inorganic deposits and effluent emissions. However, the literature contains limited information on how poor pulp washing affects ECF chemical consumption and pulp brightening. Laboratory investigations examined this topic back in 1970s with a chlorine-based sequence, such as those by Jack Histed and colleagues [13-17]. However, similar studies have not been replicated for today's ECF sequences. Such laboratory studies are laborious and time consuming to conduct. An alternative method to obtain this information is through computer simulations.

This research utilizes some steady-state models that are coupled together to simulate multistage ECF sequences. These models, once tuned with basic bleaching data, have the ability to account for the impacts of washer carryover from an interstage washer on other bleaching stages with regards to oxidant consumption, kappa number reduction, and/or brightness development.

The most interesting result from our numerical modeling was that nominal levels of (EO) washer carryover (e.g., 15%) resulted in an additional chlorine dioxide demand that was similar to the bleach demand caused by typical brownstock carryover levels (e.g., 10 to 15 kg Na_2SO_4/ton pulp) into the bleach plant.

Process engineers can modify and tune the multistage ECF models employed in this study to simulate their bleach plants to estimate how improvements in interstage washing or changes to countercurrent washing schemes can affect chlorine dioxide bleach usage.

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28. Basta, J., Andersson, L., Blom, C., et al.,"New and improved possibilities in D_{100} bleaching," *TAPPI Pulping Conf.*, TAPPI Press, Atlanta, 1992, pp. 547-553.

29. Brogdon, B.N., *TAPPI J.* 9(8): 27(2010).

30. Turner, P.A., Allen, L.H., Allen, S.L., et al., in *Pulp Bleaching: Principles and Practice* (C.W. Dence and D.W. Reeve, Eds.), TAPPI Press, Atlanta, 1996, pp. 569-596.

31. Germgard, U. and Steffies, F., "Pulp washing in a closed bleach plant, Part 2," *Pulp Washing '96*, CPPA/TAPPI, Montréal/Atlanta, 1996, pp. 31-36.

32. Kappel, J., Sbaschnigg, J., and Petschauer, F., "Improved washers for low effluent bleach plants," *Pulp Washing '96*, CPPA/TAPPI, Montréal/Atlanta, 1996, pp. 109-114.

33. Viirmaa, M., Dahl, O., Niinimäki, J., et al., *Appita J.* 55(6): 484(2002).

34. McDonough, T.J., Baromès, J.-C., Carter, B.R., et al., C.E., "Effects of washer efficiency on characteristics of effluents from D(EPO) D bleaching of a softwood kraft pulp," *TAPPI Environ. Conf.*, TAPPI Press, Atlanta, 1998, pp. 85-92.

35. Paleologou, M., Mahmood, T., Voss, R., et al., "Progressive system closure: A Canadian perspective," *Proc. Braz. Symp. Chem. Lignins Other Wood Compon.*, *7th,* Universida de Federal de Viçosa, Viçosa, Brazil, 2001, pp. 229-241.

36. Jour, P., Lindgren, K., Gutke, K., et al., *TAPPI J.* 17(6): 353(2018).

37. Parming A., Backlund B., and Bergnor, R., "A kinetic study of the reactions between dissolved organic substance and chlorine dioxide," *Intl. Pulp Bleaching Conf.*, TAPPI Press, Atlanta, 1988, pp. 161-167.

38. Rudie, A.W. and Hart, P.W., "Modeling of bleach plant washer mineral scale," *TAPPI Fall Technical Conf.*, TAPPI Press, Atlanta, 2004.

39. Rudie, A.W. and Hart, P.W., in *The Bleaching of Pulp* (P.W. Hart and A.W. Rudie, Eds.) 5th edn., TAPPI Press, Atlanta, 2012, Chap. 7, pp. 175-216.