Improving pulp yield for integrated southern hardwood kraft mills—significance and impact on chemical recovery, steam and power generation, and bleaching

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ABSTRACT: Researchers have been attempting to improve the yield of bleachable-grade kraft pulp for several decades. Wood is typically one of the major costs associated with kraft pulping. Therefore, it is typically assumed that improving pulp yield or conversely, reducing the amount of wood required to make a specific mass of pulp, is a cost-effective, lucrative endeavor. Although this may be true, it is important to understand the impact of increasing pulp yield on the interconnected processes within an integrated pulp and paper mill and to fully evaluate the cost implications on these processes. The current work employed several sets of laboratory pulping conditions and a WinGEMS model of a pulp mill, fully integrated with chemical recovery, power, and recausticization, and pulp drying islands to determine where the largest cost impact associated with improved pulp yield may be experienced.

Application: This work can give new engineers better understanding of interactions between different operational departments within a mill. It may also be used to develop an improved analysis of the true economic impact associated with enhancing pulp yield.

Of all operating costs associated with making market-kraft pulp or paper, the largest one by far is the cost of the wood [1]. In a 2009 study of Canadian mills, the Canadian Industry Statistics department determined that labor constituted 12% of the total production costs; water and fuel consumed 14% of the total manufacturing costs, and materials and supplies took up the remaining 74% of manufacturing costs [2]. Capital costs were not considered in this analysis. Medium-size mills producing 1000 tons/day of pulp can routinely spend more than US$3,000,000 per month on wood.

Unfortunately, the kraft pulping process is not a particularly good steward of this expensive commodity. Water accounts for about half of the cost of wood and frequently, the pulping process dissolves about half of the dry solids. Even more wood mass is lost in the bleaching process. The net result is that about 4 tons of purchased wood chips are required to produce a single ton of good pulp. Because the cost of the wood is so high and the kraft process uses it so poorly, several symposia have focused on breaking the yield barrier [3,4]; furthermore, multiple research projects have been initiated to enhance kraft pulp yield [5]. These efforts have resulted in the development of chemical pulping modifications to increase pulp yield [6]. Those modifications include the use of digester additives such as anthraquinone (AQ), polysulfide, penetrant, or various combinations of these materials [7]. Equipment suppliers have also worked to improve brownstock pulp yield through modifications in the cooking process, such as rapid displacement heating (RDH) pulping [8], Downflow Lo-Solids technology [9], and compact cooking [10]. In all of those instances, only a brownstock yield increase of 1%–5% over a traditional kraft pulping process has been realized. The Agenda 2020 Technology Alliance decreed that a breakthrough process for kraft pulping would be any process that is capable of improving pulp yield by more than 5% above traditional kraft pulping methods [5]. Several of the process modifications employed depend on retarding or avoiding the peeling reaction, accelerating delignification, removing barriers to efficient mass transfer, or a combination of these actions. Polysulfide, for example, blocks peeling by oxidizing polysaccharide end groups. Anthraquinone has the same effect and has the additional advantage of being regenerated by reactions that accelerate delignification [11].

Often, these modified chemical pulping processes have a negative impact on pulp strength. In unbleached grades, increasing the yield significantly above the fiber liberation point may result in fiber damage during refining. In bleachable grades, the effects most often observed are attributable to increases in the hemicellulose content of the fibers. In addition to lower tensile strength, many of these pulps often have lower tear strength.

Also, these pulping modifications all add a significant cost to pulp manufacturing. Nonetheless, several mills have eagerly embraced the technology in efforts to reduce wood costs. In general, enhancing pulp yield is frequently viewed as a type of "holy grail" of pulping research [6]. Recent efforts have attempted to break several pulping paradigms and dramatically change traditional pulping and bleaching methodologies to obtain higher-yield bleached kraft pulp [12].

Some of the costs associated with increasing pulp yield—such as purchasing an additive (e.g., AQ, a penetrant, or a combination of the two [14]) to add into the digester— are easily identified. Typically, the benefit (i.e., increased pulp yield) is more difficult to measure on a monthly or quarterly basis because the wood has a significant month-to-month variability [13, 14] and the yield improvements are frequently small.

Other costs associated with improving pulp yield may be somewhat removed from the initial area of impact; thus, they are more difficult to account for in a typical pulping experiment and even more difficult to correlate to increased pulp yield within a mill environment. For instance, a mill's attempts to increase yield by increasing the kappa number of the pulp will decrease the amount of black liquor solids going to the recovery boiler and ultimately reduce the steam production from that boiler. In some cases, the lost steam will have to be produced by burning more fuel in the power boiler, which represents a direct cost. If the steam usage profile in a mill is substantially altered by attempts to improve pulp yield, the amount of extraction steam obtained from the turbines may be reduced and result in decreased electrical production. Other peripheral areas of the mill (e.g., the lime kiln) may experience reductions in operating costs due to decreased white liquor demand.

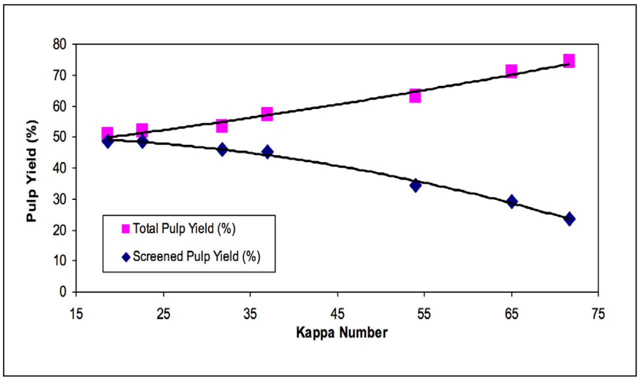
It is important to understand that the current work did not actually evaluate the cost impact of improving yield. Rather, the impact of yield changes and different methods of obtaining pulp yield were determined for several of the key operating conditions in various areas of the entire mill. Actual costs were not used because different mills have different cost constraints and raw material costs. By only dealing with the magnitude of process variable changes, each mill may employ its own cost structure to determine the optimal yield-cost performance for its location.

Also of note, increased pulp yield has a very different—and typically substantially improved—value if it is used to displace purchased pulp or to incrementally increase production of value-added paper grades. Increased production is only valuable if it can be sold without having a negative impact on the supply-and-demand cost structure of that grade. The impact or value for these scenarios were beyond the scope of the current work and were not evaluated.

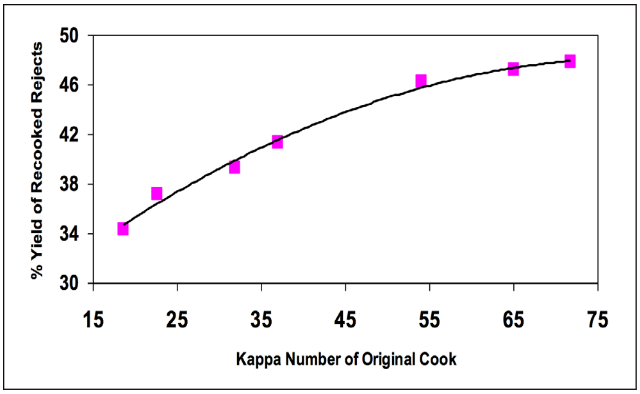
An evaluation of how each of these methods of improving or altering pulp yield affected the mill's environmental footprint was also beyond the current scope. For instance, increasing the kappa number going to the bleach plant will increase the organic effluent loading of the mill. Several other environmental performance issues could potentially arise from some of the evaluated scenarios. It will be important to fully investigate the environmental impact of any change before performing that change within a specific mill [15].

EXPERIMENTAL METHODS

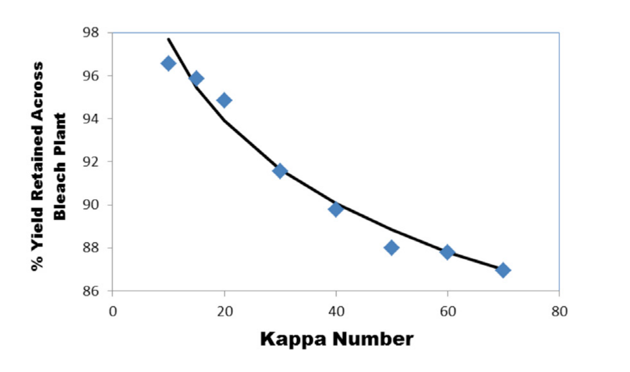
The current work attempted to determine some of the costs and benefits associated with increasing pulp yield through the use of a comprehensive WinGEMS process model of an integrated pulp and paper mill; the associated evaporation, recovery, and recausticizing islands were included in the model. Laboratory pulping experiments were performed in an M/K pilot digester (M/K Systems; Peabody, MA, USA) using mill-mixed southern hardwood chips and mill white liquor. A liquor-to-wood ratio of 4:1 was employed for this work. White liquor charge (12%–18% effective alkali), maximum cooking temperature, and time at temperature were varied to obtain pulps with kappa numbers ranging from about 14 to 70. Black liquor samples were collected from these cooks and analyzed for residual alkali content, higher heating value (HHV), and pounds of black liquor solids per ton of pulp produced (BLS/ton). Pulps were well washed with distilled water and the total pulp yield was determined for each cook. The pulps were mechanically disintegrated in a bucket with a lightning mixer for 5 min,



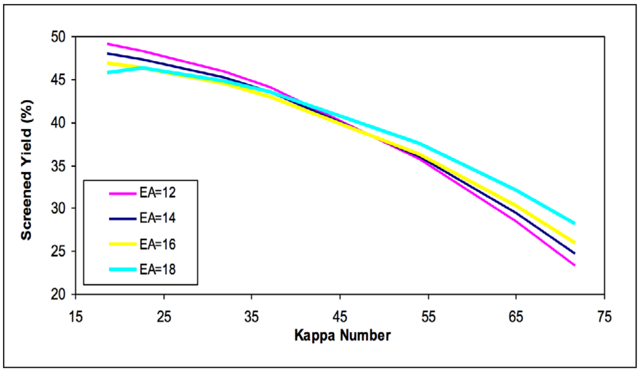
1. Total and screened pulp yield for the M/K pilot digester cooks performed.



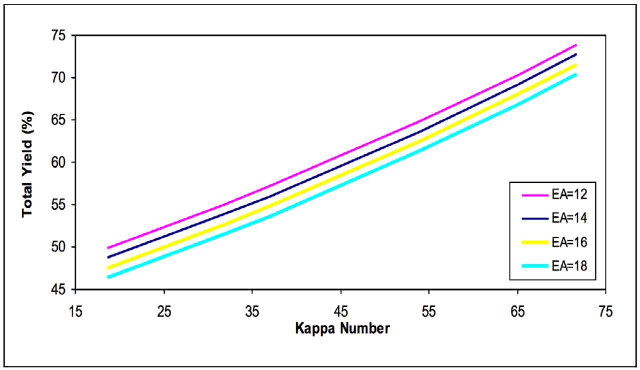
2. Yield of recooked rejects cooked to kappa no. 15–16 as a function of the initial brownstock kappa number from which the rejects were obtained.



3. *Yield loss as a function of kappa number across an XD(EP)DD bleaching sequence.*



5. *Impact of effective alkali charge on screened pulp yield [16].*



4. *Impact of effective alkali charge on total pulp yield [16].*

then screened on a 0.25-mm slotted screen. The percent accepts and rejects were determined to be the percentage of pulp passing through and retained on the screen, respectively. The total and screened pulp yields are shown in **Fig. 1**. Selected samples of pulp rejects were then recooked to about kappa no. 15–16 and basically zero rejects to determine the yield of recooked rejects. The results of those experiments are shown in **Fig. 2**. The kappa number of the accept pulps was determined using TAPPI method T-236 om-99 “Kappa number of pulp.”

Small portions of these pulps were then bag bleached with an XD(EP)DD bleaching sequence to obtain about 85–88 GE brightness. Bleach chemical addition was varied to obtain the required brightness. Each bleaching experiment was performed in triplicate and the reported yield loss results were averaged. Yield loss across the bleaching sequence was determined gravimetrically and is shown in **Fig. 3**.

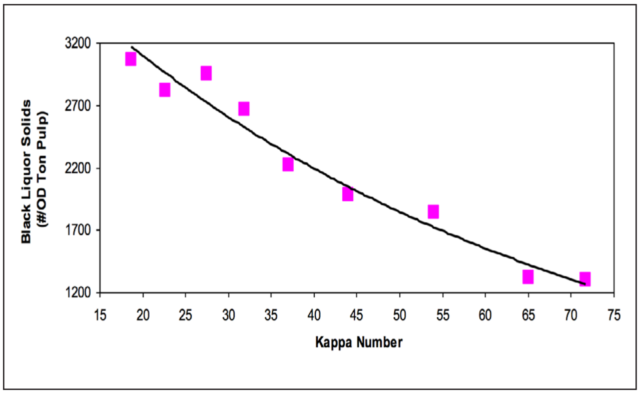
Literature data were also used to determine the impact of differing cooking conditions on the total and screened pulp yield [16]. The impact of white liquor charge on pulp yield was of particular interest for this study. In general, provided sufficient residual alkali was retained, use of a lower alkali charge and a higher H-factor to obtain a specific kappa number increased the total pulp yield, as shown in **Fig. 4**.

Upon examination of the impact of increased alkali charge on the amount of rejects and shives produced, it was generally determined that a higher alkali charge produced less rejects at a given kappa number. Also, the screened yield of the pulp produced altered significantly at lower kappa numbers, crossed at intermediate kappa numbers, and again diverged at ultrahigh kappa numbers. The screened yield results for various kappa-number pulps produced with varying effective alkali charges [16] is shown in **Fig. 5**.

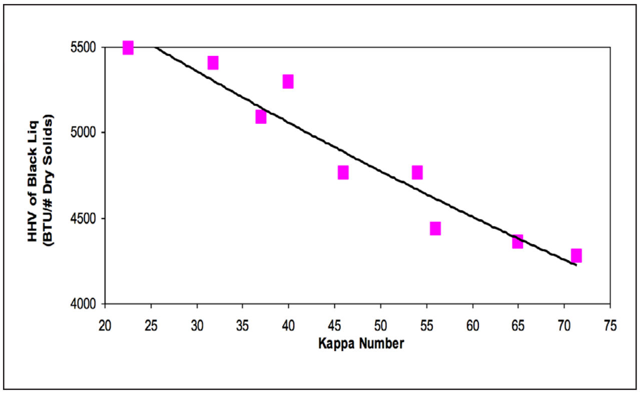
The data on total yield, screened yield, and kappa number were used to control the digester cooking sequence in the WinGEMS model. Those conditions resulted in various process model constraints, shown in **Table I**. The steam demand from the power boiler was set to satisfy the process steam

Pulp production	o.d. tons/day	1500	1500	1500	1500
Effective alkali on wood	%Na_2O	18	18	18	18
Wood moisture	%	52.0	52.0	52.0	52.0
Wood carbohydrates	%	72.0	72.0	72.0	72.0
Wood lignin	%	28.0	28.0	28.0	28.0
Kappa target		18.6	37.0	54.0	71.7
Yield target	%	49.9	57.1	64.8	73.9
Lignin removal		0.95	0.89	0.81	0.72
Carbohydrate removal		0.33	.025	.017	0.08
Pulp yield	%	50.0	57.2	65.0	74.1
Kappa number		18.6	37.0	54.0	71.7

I. *Process constraints obtained from the experimental data used in the WinGEMS model (conditions for 18% effective alkali only).*



6. Amount of black liquor solids per ton of pulp produced as predicted by the WinGEMS model (solid line) and measured from laboratory data (squares).



7. Higher heated value of black liquor as predicted by the WinGEMS model (solid line) and measured from laboratory data (squares).

conditions and provide a constant 250 kPa/h of steam to the turbine condenser. The model was run to various kappa numbers and allowed to converge using the constraints shown in Table I. No attempt was made to control the black liquor properties resulting from these constraints; rather, the programming within the specific functional WinGEMS blocks was allowed to run without external manipulation. The model predicted BLS/ton, and the predicted black liquor HHV were obtained over the range of kappa numbers studied in the laboratory and compared to the actual laboratory values. **Figures 6** and **7** show the comparison of the laboratory values and the model predicted results for the BLS/ton produced and the black liquor HHV, respectively. As shown in these figures, excellent agreement was obtained.

Modeling conditions employed

On the basis of the excellent agreement between the integrated mill model and laboratory predictions over a wide range of kappa numbers, applied effective alkali, and pulp yields, it was determined that the model was sufficiently robust to use for parametric studies. Modeling was performed under five distinct sets of operating conditions. The first set of conditions simply varied the applied effective alkali (12%–18%) and H-factor required to obtain the same kappa-number pulp. Literature data were used to determine the impact of effective alkali on pulp digester yield and rejects [16]. Strength properties of the resulting bleached pulp were not evaluated. Each of the models used in this set of studies assumed a constant bleached pulp production of 1500 o.d. tons/day.

The second set of conditions allowed the kappa number, resulting pulp yield, and percentage of screening rejects to increase. Laboratory numbers were used to establish these conditions. It was assumed that some form of novel pulping process similar to one reported earlier in the literature [12] would be used to render these rejects into usable fiber with no yield loss ahead of the bleach plant. An energy penalty of 125 kW·h/ton of brownstock pulp produced was added to the model to account for additional processing of the rejects. The kappa number for this set of model studies was varied from about 18 to 70. These conditions were repeated for 12%, 14%, 16%, and 18% effective alkali on wood addition rates. Each of the models used in this set of studies assumed a constant bleached pulp production of 1500 o.d. tons/day.

The third set of conditions assumed that the resulting screen rejects could not be successfully used without further yield-consuming processing, such as recooking. The screen rejects were separated from the acceptable fiber stream and repulped separately to obtain pulp with kappa number of about 15–16 with no rejects, using the yield conditions shown in Fig. 2. The pulp from the recooked rejects was combined with accepts from the original screened pulp, and a modified kappa number of the blended pulp was determined using mass weighted averages of accepts and recooked pulps. This blended pulp was sent to the bleach plant. Models were run for initial digester kappa numbers ranging from about 17 to 65. Each of the models used in this portion of the work produced a constant amount of bleached pulp going to the paper machine.

The fourth set of model studies examined the impact of using digester additives, such as AQ, on the back-end cost structure. Data for AQ impact on kappa and yield were obtained from the literature [16]; the use of AQ was assumed to increase brownstock pulp yield by 2 points and the amount of rejects by 0.5 points. When examining the additional costs and benefits associated with the use of digester additives, it will be critical to count the actual cost of the additive in the calculation. It will also be important to determine whether the additive has a negative impact on the final strength properties; however, the strength issue was beyond the scope of the current work. Each of the models used in the AQ evaluation assumed a 17–18 kappa no. brownstock pulp and a constant production rate of 1500 o.d. tons/day bleached pulp going to the paper machine.

The final set of conditions evaluated the impact of brownstock pulp production compared with bleached pulp production. For this evaluation, it was assumed that some form of yield-retaining treatment had been employed to render the initial rejects into usable fiber. This study condition was conducted to highlight the importance of understanding the desired results and the attention to detail that is required when comparing various pulping methodologies and conditions. When simply using brownstock pulp production as a production metric, the optimal cost structure may be different than when using bleached pulp production as the optimization metric when evaluating the impact of yield-altering treatments on the mill's total cost structure. The current study evaluated the impact of different methods of obtaining the same total amount of pulp going to the bleach plant or to the paper machine. This was chosen as the model evaluation method so the reader could easily evaluate the impact of changing conditions per ton of pulp produced. In a performing mill, the cost structure might be improved by consuming the same amount of wood in the digester and using the increased yield to produce more paper. For the current work, it was decided that such an approach—although potentially the approach used by a mill—would be more difficult for the reader to evaluate. Therefore, each evaluation used in this portion of the study fixed the final pulp production to 1500 o.d. ton/day of pulp (brown or bleached). Of note, digester yield referred to the mass of solid material (brown fiber and rejects) leaving the digester, while paper machine yield referred to fully screened and bleached fiber leaving the bleach plant.

REVIEW OF MODEL RESULTS

Pulping to the same kappa number while allowing applied effective alkali to change

The first parametric study simply altered the applied effective alkali used to pulp to the same kappa number and the same bleached pulp production. Literature data were used to obtain the impact of effective alkali changes on brownstock yield and rejects content [16]. Figures 4 and 5 show these changes. When the yield and reject changes were placed into the model, it was determined that simply changing the applied effective alkali from 18% on wood to 12% on wood potentially could result in about a 7% reduction in green wood, a decrease of about 10% in the amount of electrical power available to sell, a decrease in makeup lime of about 38%, and a decrease in lime kiln fuel demand of about 37%. A substantial increase of about 69% in the amount of biomass required in the power boiler was also required to make the amount of steam needed to produce and dry the resulting fiber. The absolute values for these and other major process parameters are presented in **Table II**.

As the paper machine yield is increased, the amount of wood entering the digester is decreased because the model fixes the total bleached pulp production to 1500 bleached o.d.

Kappa number		17.9	17.9	17.9	17.9	24.6	24.6	24.6	24.6
Digester yield	% on o.d. wood	46.3	47.4	48.6	49.8	48.8	50.0	51.1	52.3
Effective alkali	% on o.d. wood	18	16	14	12	18	16	14	12
Cook temperature	°F	339	339	339	339	329	329	329	329
Yield to paper machine	% on o.d. wood	43.5	44.5	45.6	46.7	43.7	44.3	45.2	46.2
Green wood	tons/day	7192	7015	6847	6687	7155	7061	6912	6769
Bleaching Chemicals									
ClO_2	tons/day	46.47	46.47	46.47	46.47	56.83	56.83	56.83	56.83
NaOH	tons/day	15.18	15.18	15.18	15.18	17.54	17.54	17.54	17.54
H_2O_2	tons/day	4.76	4.76	4.76	4.76	4.84	4.84	4.84	4.84
Power, Recovery, Lime Kiln									
Black liquor solids	lb/ton bleached pulp	3708	3420	3146	2884	3666	3454	3195	2946
Black liquor HHV	Btu/lb BL	5803	3985	6190	6422	5728	5911	6111	6337
Recovery steam	kPa/h	957.2	919.9	884.0	849.4	930.2	913.9	883.0	853.0
Power boiler steam	kPa/h	62.0	76.7	91.0	105.0	96.7	97.5	108.1	118.5
Biomass required	tons/day	304.0	376.2	446.3	515.1	474.3	478.3	530.0	581.3
Turbine generation	MW	73.95	72.57	71.21	69.91	74.7	73.66	72.36	71.11
Power used	MW	40.03	40.03	40.03	40.03	40.19	40.25	40.26	40.27
Power sold	MW	33.92	32.54	31.18	29.88	34.50	33.41	32.10	30.84
Lime kiln fuel	tons/day	105.1	90.9	77.4	64.5	106.4	94.1	80.8	68.0
Kiln fuel heat content	BTU/lb	17460	17460	17460	17460	17460	17460	17460	17460
Lime make-up	tons/day	21.6	18.7	15.9	13.3	21.9	19.3	16.6	14.0

II. Impact on wood of altering the applied effective alkali to pulp to the same kappa number and bleached pulp production (two different kappa numbers evaluated).

Kappa number		17.9	24.6	48.9	64.1
Digester yield	% on o.d. wood	49.8	52.3	62.7	70.2
Effective alkali	% on o.d. wood	12%	12%	12%	12%
Cook temperature	°F	339	329	305	305
H-factor		1000	600	200	130
Kappa number to bleach plant		17.9	24.6	49.0	64.1
Yield to paper machine	% on o.d. wood	47.0	48.6	55.5	61.0
Green wood	tons/day	6648	6434	5628	5121
Bleaching chemicals					
ClO_2	tons/day	46.49	57.20	97.63	123.33
NaOH	tons/day	15.19	17.62	26.73	32.46
H_2O_2	tons/day	4.76	4.84	5.08	5.17
Power, Recovery, Lime Kiln					
Lime kiln fuel	tons/day	63.70	61.51	53.31	48.18
Kiln fuel heat content	Btu/lb	17460	17460	17460	17460
Lime make-up	tons/day	13.1	12.7	11.0	9.9
Black liquor solids	lb/ton bleached pulp	2850	2653	1943	1523
Black liquor HHV	Btu/lb BL	6420	6326	5873	5443
Recovery steam	kPa/h	839.4	768.0	513.1	363.9
Power boiler steam	kPa/h	111.7	174.0	394.3	521.8
Biomass required	tons/day	547.7	853.6	1933.9	2559.4
Turbine generation	MW	69.73	69.47	68.21	67.21
Power required	MW	40.00	40.00	40.00	40.00
Power sold	MW	29.72	29.46	28.21	27.20
New method rate*	tons rejects/h	0.79	8.08	38.26	58.37
New method power needs*	MW	0.11	1.17	5.80	9.02
Adjusted power demand	MW	40.12	41.17	45.81	49.02
Adjusted power sold	MW	29.61	28.30	22.40	18.18

*Note the terms new method rate and new method power are representative of the process to convert rejects into usable fibers. See [8] for additional details.

III. Important process conditions resulting from increasing fiber yield via increasing the kappa number of pulp using applied effective alkali of 12% on o.d. wood. Each set of conditions assumed a constant bleached production of 1500 o.d. tons/day.

tons/day of fiber. As the amount of wood decreases, the absolute mass of white liquor decreases, resulting in decreased BLS, decreased lime demand, and decreased lime makeup. Because several of these unit processes are intimately connected with the specific operational condition of several other unit processes, the use of a comprehensive model is an excellent method to evaluate the ultimate impact a change in one area will have on other areas of the mill.

Cooking to high kappa numbers with rejects converted into usable fiber—constant bleached pulp production

These process models assumed rejects from the pulp mill were separated in the screen room and processed via novel pulping methods [12] to produce usable fiber with no additional yield loss. Laboratory data were used to establish the relationship between kappa number and brownstock yield employed in the model. An energy penalty of 125 kW·h/ton of brownstock pulp processed was included in the model to account for various rejects processing methods.

Significant digester yield improvement resulted from increasing the kappa number of the pulp. Significant increases (although lower than the digester yield increases) in the final bleached yield going to the paper machine were also noted. As more lignin and carbohydrates were diverted from the black liquor into the resulting fiber (reduced BLS/ton of pulp and lower HHV of black liquor), the steam generation in the recovery boiler dropped significantly. As a result of reduced

Kappa number		17.9	24.6	48.9	64.1
Digester yield	% on o.d. wood	46.3	48.8	59.2	66.7
Effective alkali	% on o.d. wood	18%	18%	18%	18%
Cook temperature	°F	339	329	305	305
H-factor		1000	600	200	130
Kappa number to bleach plant		17.9	24.6	49.0	64.1
Yield to paper machine	% on o.d. wood	43.7	45.3	52.4	58.0
Green wood	tons/day	7149	6895	5960	5389
Bleaching chemicals					
ClO_2	tons/day	46.49	57.20	97.63	123.33
NaOH	tons/day	15.19	17.62	26.73	32.46
H_2O_2	tons/day	4.76	4.84	5.08	5.17
Power, Recovery, Lime Kiln					
Lime kiln fuel	tons/day	104.12	100.21	85.90	77.15
Kiln fuel heat content	Btu/lb	17460	17460	17460	17460
Lime make-up	tons/day	21.4	20.6	17.7	15.9
Black liquor solids	lb/ton bleached pulp	3669	3424	2556	2050
Black liquor HHV	Btu/lb BL	5800	5707	5261	4859
Recovery steam	kPa/h	946.6	865.4	579.4	414.6
Power boiler steam	kPa/h	68.8	137.8	378.1	514.8
Biomass required	tons/day	337.5	676.1	1854.6	2524.9
Turbine generation	MW	73.75	73.36	71.48	70.08
Power required	MW	40.00	40.00	40.00	40.00
Power sold	MW	33.74	33.35	31.48	30.08
New method rate*	tons rejects/h	0.00	5.97	32.65	51.05
New method power needs*	MW	0.00	0.86	4.95	7.89
Adjusted power demand	MW	40.00	40.87	44.95	47.89
Adjusted power sold	MW	33.74	32.49	26.53	22.19

*Note the terms new method rate and new method power are representative of the process to convert rejects into usable fibers. See [8] for additional details.

IV. Important process conditions resulting from increasing fiber yield via increasing the kappa number of pulp using applied effective alkali of 18% on o.d. wood. Each set of conditions assumes a constant bleached production of 1500 o.d. tons/day.

high-pressure steam production in the recovery boiler, less steam was available to generate electricity in the turbines. Significant changes in green wood demand and in bleaching chemicals were also noted.

This process evaluated kappa numbers ranging from about 16 to 70. Four separate applied effective alkali values were also employed in this evaluation. For illustrative purposes, the results for 12% and 18% effective alkali were included; the process results are presented in **Tables III** and **IV**. Of note, each model was fixed to produce 1500 o.d. tons/day of bleached pulp going to the paper machines. The yield to the paper machine represented fully screened and bleached fiber, not unbleached yield entering the bleach plant or digester yield.

If a mill were located in an area with expensive electrical power, high-cost auxiliary fuel, and/or high-cost bleaching chemicals, the savings in wood would be substantially offset by the reduction in power generation and the need to produce steam in the power boiler to dry the pulp. Conversely, if a mill were located in a high-cost wood area, significant costs savings could potentially result even with the required increase in purchased power, purchased fuel, and bleaching chemicals.

Cooking to high kappa numbers with rejects being recooked—constant bleached pulp production

Another method of increasing the initial brownstock digester pulp yield is to pulp to high kappa number and reprocess the resulting rejects using some method of yield-consuming technique. For this study, it was assumed that the resulting rejects were collected and recooked to brownstock pulp with about

Kappa number	18% Applied Effective Alkali		12% Applied Effective Alkali	
	Digester Yield %	Bleach Plant Yield %	Digester Yield %	Bleach Plant Yield %
17.9	46.3	43.5	49.8	46.7
24.6	48.8	43.7	52.3	46.2
48.9	59.2	43.4	62.7	44.3
64.1	66.7	43.2	70.2	43.3

V. Digester and bleached (to paper machine) yields for a range of kappa numbers at two levels of applied effective alkali on wood (assumes rejects recooked according to values from Fig. 2). Rejects were recooked and recombined with accepts before bleaching.

Kappa number		17.9	24.6	48.9	64.1
Digester yield	% on o.d. wood	49.8	52.3	62.7	70.2
Effective alkali	% on o.d. wood	12	12	12	12
Cook temperature	°F	339	329	305	305
H-factor		1000	600	200	130
Kappa number to bleach plant		17.8	24.3	41.6	44.6
Yield to paper machine	% on o.d. wood	46.7	46.2	44.3	43.3
Green wood	tons/day	6687	6769	7048	7211
Bleaching Chemicals					
ClO_2	tons/day	46.47	56.70	85.19	90.18
NaOH	tons/day	15.18	17.51	23.94	25.06
H_2O_2	tons/day	4.76	4.84	5.02	5.04
Power, Recovery, Lime Kiln					
Black liquor solids	lb/ton bleached pulp	2884	2946	3285	3591
Black liquor HHV	Btu/lb BL	6422	6337	5960	5700
Recovery steam	kPa/h	849.4	853.0	878.0	903.8
Power boiler steam	kPa/h	105.0	118.2	180.1	231.5
Biomass required	tons/day	515.1	581.3	883.4	1135.6
Turbine generation	MW	69.91	71.11	76.77	81.47
Power used	MW	40.3	40.27	41.79	43.49
Power sold	MW	29.88	30.84	34.98	37.98
Lime kiln fuel	tons/day	64.5	68.0	86.6	102.7
Kiln fuel heat content	Btu/lb	17460	17460	17460	17460
Lime make-up	tons/day	13.3	14.0	17.8	21.1

VI. Important process conditions resulting from pulping to higher kappa number and repulping the rejects using 12% applied effective alkali on o.d. wood. Each set of conditions assumes a constant bleached pulp production of 1500 o.d. tons/day.

a 15–16 kappa number with little or no additional rejects. Laboratory data were used to determine the yield of the recooked rejects. The pulp obtained from the rejects cooks was recombined with the accept pulps from the initial digester cooks and a new kappa number was determined for the brownstock pulp being sent to the bleach plant. The new kappa number was calculated using Eq. (1):

$$\text{Kappa number} \times 0.147 = \text{wt\% lignin} \quad (1)$$

Bleach plant shrinkage was determined using the calculated kappa number to the bleach plant and the data from Fig. 3.

An interesting outcome of this set of studies was that the resulting bleached pulp yield going to the paper machines was about the same for the entire range of kappa numbers studied (17.9–64.1). Even though a substantial increase in the brownstock pulp yield was obtained from the digester at higher kappa number, the increase in reject production and the resulting yield loss during rejects processing, combined with higher yield loss across the bleach plant at higher entering kappa numbers, resulted in the final bleached pulp yield being substantially reduced from the digester yield. **Table V** presents a comparison of the yield results for 12% and 18% applied effective alkali. Note that at higher kappa number, the bleached yield was lower than at traditional kappa number.

Because of the significant amount of reprocessing

Kappa number		17.9	24.6	48.9	64.1
Digester yield	% on o.d. wood	49.8	52.3	62.7	70.2
Effective alkali	% on o.d. wood	18	18	18	18
Cook temperature	°F	339	329	305	305
H-factor		1000	600	200	130
Kappa number to bleach plant		17.8	24.4	42.9	47.9
Yield to paper machine	% on o.d. wood	43.5	43.7	43.4	43.2
Green wood	tons/day	7192	7155	7197	7226
Bleaching Chemicals					
ClO_2	tons/day	46.47	56.83	87.41	95.86
NaOH	tons/day	15.18	17.54	24.44	26.33
H_2O_2	tons/day	4.76	4.84	5.03	5.07
Power, Recovery, Lime Kiln					
Black liquor solids	lb/ton bleached pulp	3708	3666	3788	3954
Black liquor HHV	Btu/lb BL	5803	5728	5424	5215
Recovery steam	kPa/h	957.2	930.2	891.1	879.1
Power boiler steam	kPa/h	62.0	96.7	199.8	271.0
Biomass required	tons/day	304.0	474.3	979.9	1329.2
Turbine generation	MW	73.95	74.70	79.16	82.83
Power used	MW	40.03	40.19	41.44	42.79
Power sold	MW	33.92	34.50	37.72	40.05
Lime kiln fuel	tons/day	105.1	106.4	120.3	132.9
Kiln fuel heat content	Btu/lb	17460	17460	17460	17460
Lime make-up	tons/day	21.6	21.9	24.7	27.3

VII. Important process conditions resulting from pulping to higher kappa number and repulping the rejects using 18% applied effective alkali on o.d. wood. Each set of conditions assumes a constant bleached pulp production of 1500 o.d. tons/day.

resulting from the need to recook rejects, a significant increase in total lime kiln demand, an increase in steam demand, and an increase in wood demand resulted from increasing the digester yield of the wood. The higher kappa number going to the bleach plant also increased the bleach chemical demand. Thus, by attempting to reduce operating costs by increasing the kappa number and reprocessing the resulting substantial amount of rejects produced in a yield-consuming process, the resulting production costs dramatically increased. **Tables VI** and **VII** show the process parameter values for attempting to recook rejects using 12% and 18% applied effective alkali. Note that the initial digester yield was substantially improved even though the bleached yield to the paper machine decreased.

Employing digester additives to enhance pulp yield

The fourth set of model analysis conditions examined the impact of adding additives to the digester to prevent kraft-peeling reactions by stabilizing the carbohydrate end groups during the pulping process. Literature data suggested that adding AQ to the cook could potentially increase the carbohydrates at a given kappa number sufficiently to result in a 2-point increase in pulp yield [16]. The same literature source also suggested that rejects resulting from the application of AQ would increase roughly 0.5 points [16]. The current work simply used the results of this published study. Other literature sources suggested that using AQ does not increase rejects [17,18]. No effort was made to account for the accelerated delignification kinetics that may result from using AQ [19] by reducing process temperatures, reducing the applied alkali charge [20], or altering the H-factor. These data were not included in the literature source. The current study simply employed the data from [16] and in no way suggested the results are typical of an AQ application in a specific mill.

The models were run for kappa no. 17.9 pulp at four different applied effective alkali levels, both with and without AQ. In all cases, the amount of wood required to produce 1500 o.d. tons/day of bleached pulp decreased with the use of AQ. The electric power available for sale did not substantially change, nor did the amount of bleaching chemicals required to bleach the pulp. In all cases, a substantial increase in the amount of biomass required to make the total volume of steam required resulted with the use of AQ. Most of the other important parameters remained unchanged. It would be important to evaluate the cost of the AQ and the cost of the increased biomass against the reduction in wood resulting from AQ use to determine the total cost benefit of adding AQ to the digest-

Additive		None	AQ	None	AQ	None	AQ	None	AQ
Kappa number		17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9
Digester yield	% on o.d. wood	46.3	48.3	47.4	49.4	48.6	50.6	49.8	51.8
Effective alkali	% on o.d. wood	18	18	16	16	14	14	12	12
Cook temperature	°F	339	339	339	339	339	339	339	339
H-factor		1000	1000	1000	1000	1000	1000	1000	1000
Kappa number to bleach plant		17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8
Yield to paper machine	% on o.d. wood	43.5	44.1	44.5	45.0	45.6	46.1	46.7	47.1
Green wood	tons/day	7192	7083	7015	6948	6847	6785	6687	6629
Bleaching Chemicals									
ClO_2	tons/day	46.47	46.40	46.47	46.39	46.47	46.39	46.47	46.39
NaOH	tons/day	15.18	15.17	15.18	15.17	15.18	15.17	15.18	15.17
H_2O_2	tons/day	4.76	4.76	4.76	4.76	4.84	4.84	4.84	4.84
Power, Recovery, Lime Kiln									
Black liquor solids	lb/ton bleached pulp	3708	3639	3420	3390	3146	3120	2884	2863
Black liquor HHV	Btu/lb BL	5803	5746	5985	5927	6190	6127	6422	6354
Recovery steam	kPa/h	957.2	927.2	919.9	900.4	884.0	865.8	849.4	832.2
Power boiler steam	kPa/h	62.0	93.5	76.7	101.3	91.0	114.5	105.0	127.6
Biomass required	tons/day	304.0	458.7	376.2	496.7	446.3	561.7	515.1	625.9
Turbine generation	MW	73.95	74.15	72.57	72.92	71.21	71.57	69.91	70.28
Power used	MW	40.03	40.16	40.03	40.18	40.03	40.18	40.03	40.18
Power sold	MW	33.92	33.98	32.54	32.73	31.18	3.39	29.88	30.11
Lime kiln fuel	tons/day	105.1	105.02	90.88	91.80	77.35	78.41	64.46	65.63
Kiln fuel heat content	Btu/lb	17460	17460	17460	17460	17460	17460	17460	17460
Lime make-up	tons/day	21.6	21.6	18.7	18.9	15.9	16.1	13.3	13.5

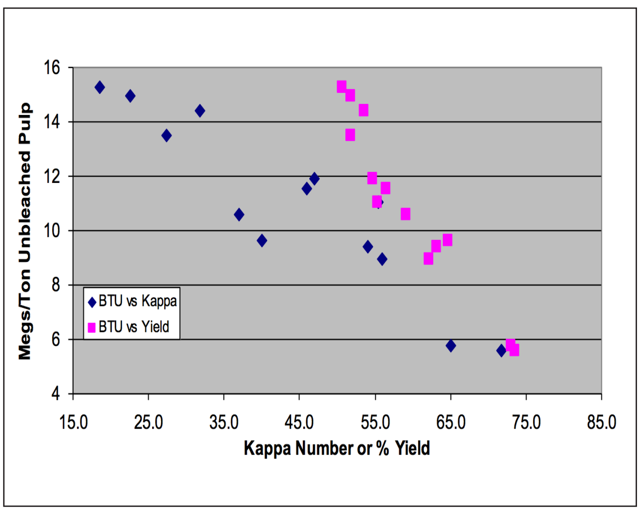
VIII. Impact of adding AQ to the digester to produce 17.9 kappa no. brownstock pulp.

er. **Table VIII** shows the results of AQ addition compared to the baseline runs without AQ.

Determining the source of yield

An evaluation of the impact of changing the carbohydrate retention in the pulp and of increasing the digester yield, by pulping to higher kappa numbers or employing lower dosages of effective alkali, on the HHV of the black liquor suggested that a significant portion of the increased yield resulted from an increase in the carbohydrate retention. Lignin has been reported to have an HHV of about 11000 Btu/lb while carbohydrates have an HHV of only about 6000 Btu/lb [21].

If lignin was lost or retained proportionally to the change in yield, a significant change in the black liquor HHV would result because lignin has a much higher HHV than hemicelluloses or carbohydrates. As more hemicelluloses are retained in the fiber, the relative contribution of dissolved lignin toward the black liquor HHV increases. Therefore, the reduction in liquor HHV with increased yield or kappa number was



8. Impact of increased digester yield or kappa number on the black liquor higher heated value.

less than would be expected. **Figure 8** shows the relative impact of increasing brownstock pulp yield or kappa number on the black liquor HHV.

Bleached vs. unbleached pulp production—importance of understanding the detailed evaluation of yield impact

When pulping to a constant bleached pulp production instead of a constant brownstock production, the difference between pulp yield with high kappa number and pulp yield with traditional kappa number are substantially reduced due to a significant increase in shrinkage across the bleach plant associated with higher kappa number pulps. As the above studies showed, a substantial increase in initial digester yield might not result in a large increase in bleached pulp yield but other changes in the back end of the mill might be substantial. Pulping to higher kappa number decreases BLS and decreases HHV of the black liquor, which results in decreased recovery boiler steam production and decreased electrical power generation. Bleaching chemical costs also substantially increase when pulps with higher kappa number are bleached.

To demonstrate the reported differences, model results obtained for 16% effective alkali on wood pulp production at four different kappa numbers were evaluated. It was assumed that 100% of the digester yield was converted into usable fiber and passed to the bleach plant in order to simplify the analysis and show the large discrepancies in results that can arise from choosing different bases for the economic analysis. The specific values are shown in **Table IX**.

Under these sets of cooking conditions, the assumption was that increasing kappa number from 17.9 to 64.1 would substantially reduce the amount of green wood needed to produce a specific amount of pulp as the digester yield increased from 47.4% to 67.9%—an increase of almost 50% for the brown pulp. The bleached pulp yield for the same two kappa-number brownstock pulps was 44.8% and 59.0% on o.d. wood, respec-

Kappa number		17.9	24.6	48.9	64.1
Digester yield	% on o.d. wood	47.4	50.0	60.4	67.9
Effective alkali	% on o.d. wood	16%	16%	16%	16%
Cook temperature	°F	339	329	305	305
H-factor		1000	600	200	130
Kappa number to bleach plant		17.86	24.60	48.96	64.13
Yield to paper machine	% on o.d. wood	44.81	46.41	53.46	59.00
Green wood	tons/day	6974	6734	5845	5297
Bleaching chemicals					
ClO_2	tons/day	46.49	57.20	97.63	123.33
NaOH	tons/day	15.19	17.62	26.73	32.46
H_2O_2	tons/day	4.76	4.84	5.08	5.17
Power, Recovery, Lime Kiln					
Lime kiln fuel	tons/day	89.99	86.70	74.56	67.16
Kiln fuel heat content	Btu/lb	17460	17460	17460	17460
Lime make-up	tons/day	18.5	17.8	15.3	13.8
Black liquor solids	lb/ton bleached pulp	3383	3155	2344	1868
Black liquor HHV	Btu/lb BL	5983	5889	5432	5021
Recovery steam	kPa/h	909.6	831.8	556.5	397.2
Power boiler steam	kPa/h	83.5	150.1	383.7	517.1
Biomass required	tons/day	409.3	736.3	1882.0	2536.3
Turbine generation	MW	72.37	72.00	70.35	69.09
Power required	MW	40.00	40.00	40.00	40.00
Power sold	MW	32.36	32.00	30.35	29.09
New method rate*	tons rejects/h	0.72	7.58	35.70	54.25
New method power needs*	MW	0.10	1.10	5.41	8.38
Adjusted power demand	MW	40.11	41.10	45.42	48.38
Adjusted power sold	MW	32.26	30.90	24.93	20.71
*Note the terms new method rate and new method power are representative of the process to convert rejects into usable fibers. See [8] for additional details.					

IX. Evaluation of four different kappa-number pulps using 16% effective alkali.

tively. The change in yield was reduced from almost 50% for the brown pulp to just over 30%. This example illustrated the importance of understanding the basis for determining the cost and savings associated with yield and how the change in both brown and/or bleached yield will affect the operating parameters that lead to improved or increased cost structures.

CONCLUSIONS

Various methods of changing pulp yield can significantly alter the cost structure of a mill's back end. Often, these changes are not directly obvious; thus, the true cost structure of alternative pulping methods and technologies may not be immediately known. If increased yield is obtained by pulping to higher kappa number, the HHV and BLS of the black liquor will decrease and result in reduced steam production from the recovery boiler. To compensate for the decreased recovery boiler steam production, increased biomass fuel will be required in the power boiler. The resulting change in the steam profile might significantly alter the electrical generation of the mill and reduce the amount of power available to sell. Changes in pulping strategies may also have significant impact on the operation of the lime kiln and result in changes in kiln fuel demands and in the amount of makeup lime required.

Pulp with increased kappa number experiences much higher shrinkage across the bleach plant and requires much higher levels of bleaching chemicals than pulp with traditional kappa number, thus mitigating some of the yield advantages seen in brownstock pulps. Therefore, it is of critical importance to evaluate the proper yield (brown vs. bleached) for the desired end use of the pulp.

The majority of the models suggested that increased brownstock pulp yield resulted in a substantial increase in hemicelluloses and cellulose (carbohydrates) relative to the changes in lignin content of the fiber. That phenomenon resulted in a slower decrease in the black liquor HHV than would be expected if the lignin and carbohydrates changed proportionally to each other.

One surprising detail of this work was that pulping to higher kappa number and reprocessing the resulting increased rejects could easily result in a loss in bleached yield even though a substantial increase in digester yield might be realized. This portion of the study detailed that any method of rejects processing has to be extremely selective and not sacrifice yield; otherwise, the overall goal of increasing bleached pulp yield might not be realized even though the mill processes a significantly higher amount of brownstock pulp.

Finally, there is a potential for cost savings associated with burning power boiler fuel over processing black liquor. The higher efficiency associated with the power boiler may result in an improved cost structure over processing more liquor or higher-HHV liquor in the recovery boiler. That situation would be extremely mill specific and would require an excellent understanding of local mill costs to determine. **TJ**

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ABOUT THE AUTHORS

For several years, research has been focused on improving pulp yield. Breaking the kraft pulp yield barrier was even stated as a major goal in the Department of Energy's Agenda 2020 Roadmap. Methods of enhancing yield tend to have an impact on other areas of the mill. Our work was an attempt to elucidate the magnitude and direction of that impact on the other areas of the mill.

The current work used an extensive amount of laboratory pulping and bleaching work in conjunction with published data for various methods of enhancing wood yield. These data were used to supply operating conditions for different model scenarios employed to determine the impact of altering wood yield on other areas of the mill. Obtaining complete data sets from literature and other sources sufficient for application into the mill model was difficult. Also, developing a full-scale mill model was an initial hurdle that had to be overcome.

The most surprising aspect of this work was the realization that under certain pulping scenarios, the recycling of knots and rejects back to the digester could actually lower the brownstock yield.

Mills now have an improved understanding of the impact of increasing yield on other unit operations within the mill structure. These data will allow for better-informed decision making regarding the financial impact of a yield-enhancing scheme.

Although the current work provides an excellent primer on the topic, improved, mill-specific model conditions would need to be evaluated to fine-tune the efforts for specific mills.

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